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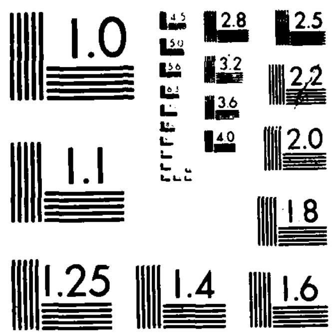

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CHAPTER 1 INTRODUCTION

Since the advent of the jet aircraft, noise control at and around an airport has become a prime concern to many local communities. To meet the ever increasing volume of air traffic, airlines are putting larger planes into operation and increasing the numbers of flights. These actions only serve to increase the total amount of noise generated at an air installation. Community demands for quieter air operations have spawned the development efforts of quieter engines, government sponsored noise abatement programs, noise certification requirements of foreign and domestic aircraft, and proposals of airport relocations as extreme as the littoral airport proposed for construction 8 miles offshore in San Pedro Bay, California, all for the sake of quiet. Although these efforts are commendable, they alone cannot satisfy the requirements of a quiet environment for people who choose to build near an airport. For example, much of the noise produced by an aircraft is a result of the large shear stresses established within the air itself in the immediate vicinity of the jet exhaust stream. Such phenomena cannot be changed by the efforts of man. Consider the level of quiet for a commercial building such as the airport hotel. Such a structure must be able to provide sufficient noise attenuation to provide a

comfortable rest environment for its patrons. The importance of the engineer's role, in conjunction with the above mentioned programs, is readily apparent. He is obligated to provide his client with an environment sufficiently quiet for the use of the building, and as quiet as is commensurate with the budget. To do this, he must be aware of the following:

1] The fundamentals of sound,

2] and the various metrics available to measure the affects of aircraft noise.

The metrics available for use can be further classified as:

1] Single Event Maximum Sound Level

2] Single Event Energy Dose

3] Cumulative Time Metrics

4] and Cumulative Energy Average Metrics.

These factors are the subject of and constitute the organization of this special topic report.

MEASURING THE ANNOYANCE

OF AIRCRAFT NOISE

by

Capt Russell K. Marcks

M.S., University of Kansas, 1986

Submitted to the Special Study Advisory Committee in partial fulfillment of the requirements for the degree of Master of Science with a major in Architectural Engineering.

Thomas Scott Dean

Professor in Charge

Clay Belcher

Ronald N. Helms

Committee Members

Ronald N. Helms

For the Department

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CHAPTER 2 FUNDAMENTALS

2.1 PROPERTIES OF SOUND

To understand the various noise metrics used to rate the annoyance potential of aircraft, one must first understand the basic properties of sound. Sound may be produced in many ways but is usually established by some vibrating body. These vibrations cause very small pressure fluctuations in the air. If these pressure fluctuations are detected by the human ear, they're perceived as sound. We can classify this sound as being wanted, desirable, or unwanted. It is this unwanted sound we normally refer to as noise.

When sound is produced, it is propagated in the form of a longitudinal wave. This is best described by making an analogy to the ripples produced when tossing a pebble into a pond of water. The crest of each wave can be likened to the compression stage of a sound wave while the valley is the decompression or rarefaction stage. The distance between any two adjacent crests is the wavelength. The number of these waves, or cycles, produced each second is the frequency of the sound in cycles per second; more commonly referred to as hertz. The audible range of a healthy young person is typically 20 Hz to 20,000 Hz. The frequency and the wavelength are related by the expression:

$$\lambda = \frac{c}{f}$$

where: λ=wavelength
f=frequency
c=speed of sound

We can also relate frequency 'f' to the angular frequency, 'ω', by the expression $f=\omega/2\pi$. By making a substitution for 'f', we can write:

$$\lambda = \frac{2\pi c}{\omega} = \frac{2\pi}{k}$$

where: $k \equiv$ wave number $[ft^{-1}]$

The significance of the wave number will be discussed later. Figure 2.1 is a graphic portrayal of sound waves.

The height of each wave is the pressure amplitude and is partially responsible for the subjective sensation of loudness. If we were able to install some pressure sensitive device some distance from the point of impact of the pebble, we could measure the pressure of a ripple of water at that point. The same is true of a sound wave; and the human auditory system is such a pressure sensitive device. The human ear will detect sound pressures as low as 2.9×10^{-9} psi. This is known as the threshold of hearing and commonly expressed in SI units as 0.00002 Pascals [Pa]. The maximum sound pressure a human can tolerate is 20 Pa, commonly referred to as the threshold of pain. Note the difference in magnitude of

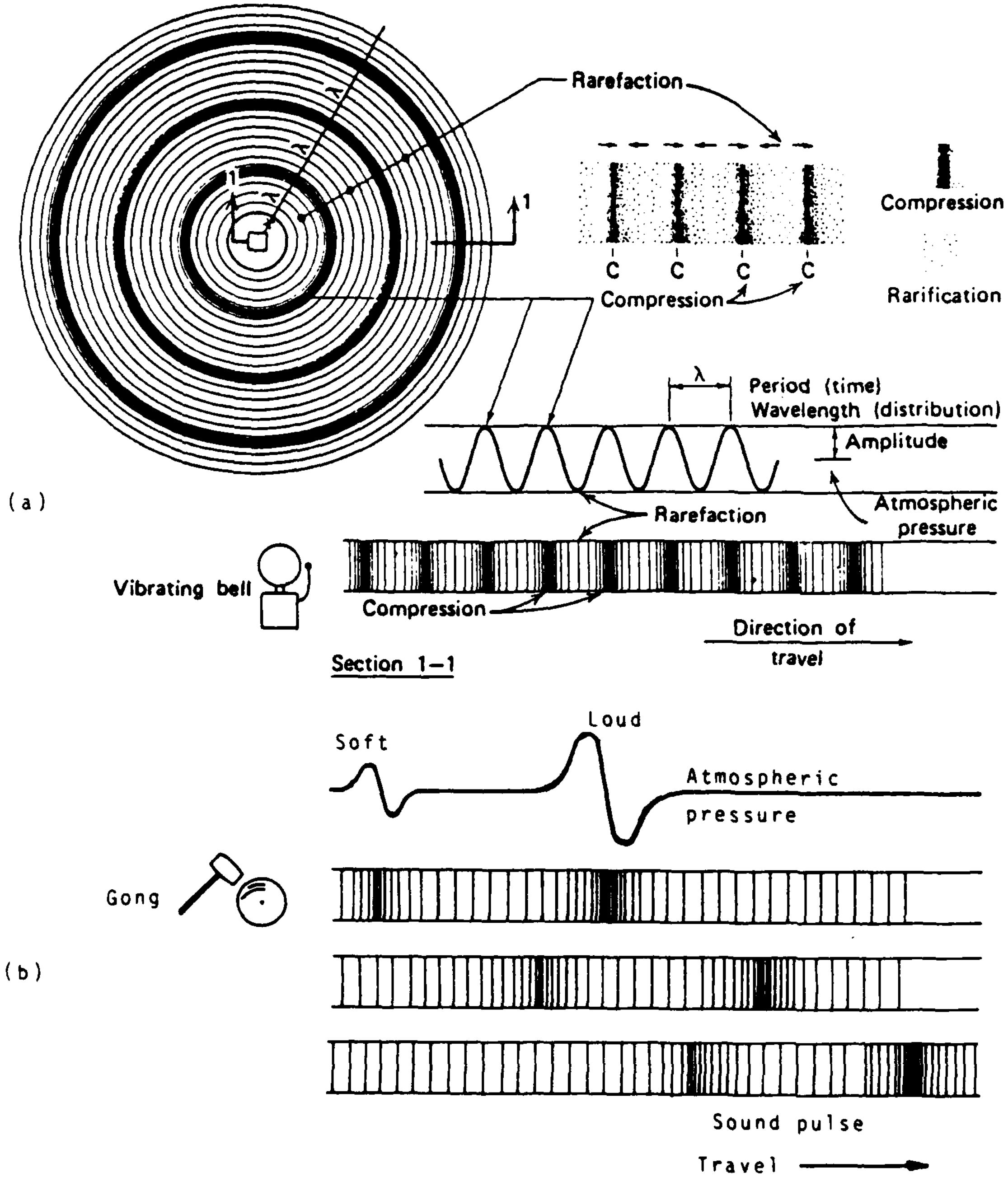


Figure 2.1 Sound waves resulting from: (a) a constant vibration (b) two impulses of differing magnitude.

these numbers is on the order of one million. Working with numbers of this magnitude can be very cumbersome. It's also difficult to maintain an intuitive feeling of loudness. For these reasons, the decibel scale was developed.

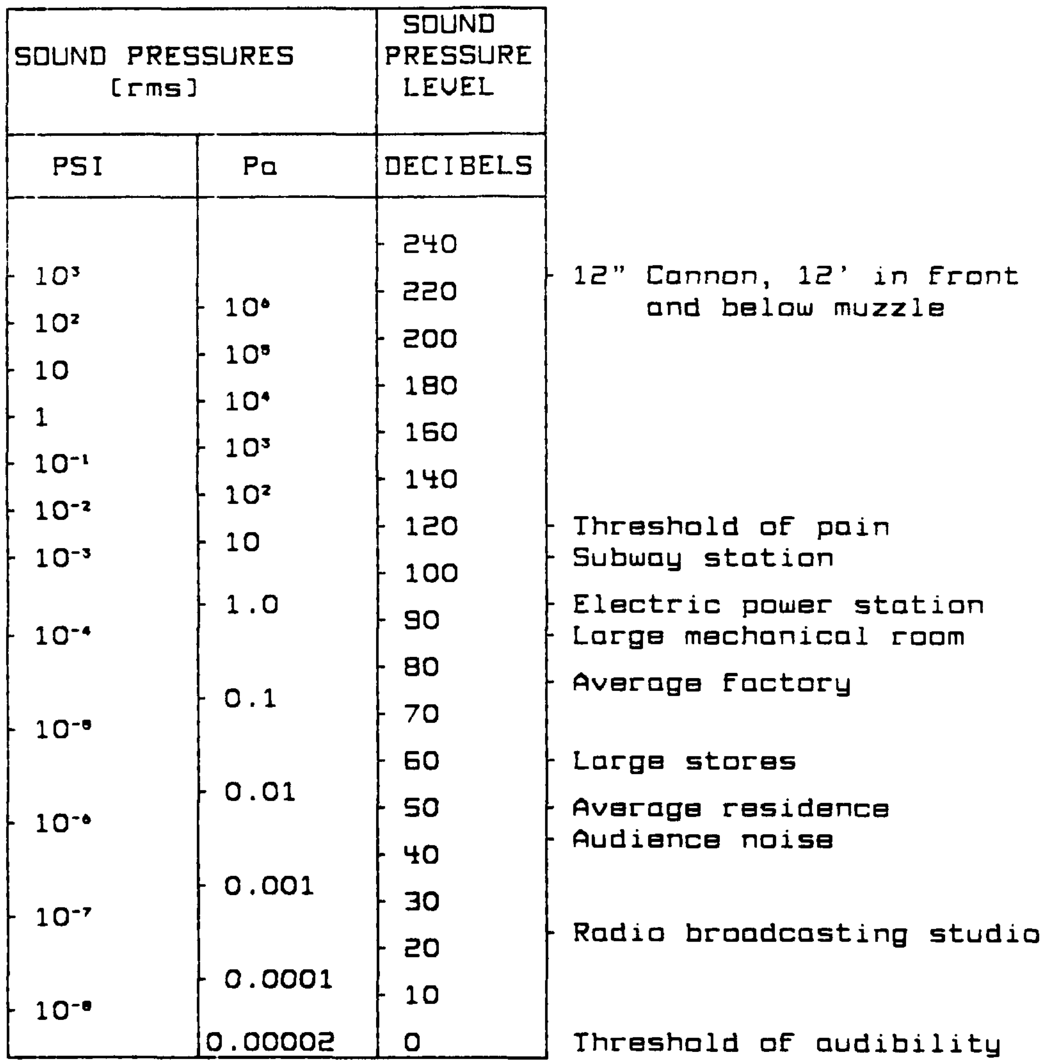


Figure 2.2 Sound pressures and levels of everyday noises

The decibel [dB] scale, illustrated in figure 2.2, is a measure of sound pressure level [SPL] and represents a ratio of a sound pressure to some reference pressure. The internationally accepted reference standard is the threshold of hearing. Sound pressure level is expressed as:

$$SPL=20Log_{10}[P/P_o]$$

where: P=sound pressure to be measured

P_o=.00002 Pa

Since the decibel is logarithmic, an 80 dB SPL isn't twice as loud as a 40 dB SPL. Using the above equation, or referring to figure 2.2, it's easy to verify 80 dB has a sound pressure 100 times as great as 40 dB! Doubling the sound pressure only results in a 6 dB increase in sound pressure level. It's also important to note the addition of two sound pressure levels is not algebraic. To add two or more sound pressure levels, use the relation:

$$SPL=10Log_{10}[10^{dB/10}+10^{dB/10}+...+10^{dB/10}]$$

A convenient alternative is provided in figure 2.3.

Occasionally, it may be necessary to subtract sound levels. This may occur if you know the sound level in an environment with a certain machine running and wish to calculate the contribution of the machine. To do this, you must subtract the ambient sound level [sound level in room with machine off] from the total sound level with

the machine running. The equation for subtracting sound levels is similar to the one above.

$$SPL=10Log_{10}[10^{dB/10}-10^{dB/10}-\ldots-10^{dB/10}]$$

Difference between levels to be added/subtracted	Decibels to be added to higher of two levels	Decibels to be subtracted from higher of two levels
0	3.01	——
0.5	2.76	9.64
1.0	2.54	6.87
1.5	2.32	5.35
2.0	2.12	4.33
2.5	1.94	3.59
3.0	1.75	3.02
3.5	1.60	2.57
4.0	1.45	2.20
4.5	1.31	1.90
5.0	1.18	1.65
5.5	1.08	1.44
6.0	0.97	1.26
7	0.78	0.97
8	0.63	0.75
9	0.51	0.58
10	0.41	0.46
11	0.33	0.36
12	0.27	0.28
13	0.21	0.22
14	0.17	0.18
15	0.14	0.14
16	0.11	0.11
17	0.09	0.09
18	0.07	0.07
19	0.06	0.06
20	0.05	0.04
24	0.02	0.02

EXAMPLE: Add a 50 dB noise to 45 dB ambient. The difference between the two levels is 5 dB. Refering to column two, add 1.18 dB to the highest level. Thus, 50 dB + 1.18 dB = 51.18 dB combined level.

EXAMPLE: Subtract an ambient level of 45 dB from a total level of 51 dB. The difference between the two levels is 5 dB. Refering to column three, subtract .97 dB from the highest level. Thus, the contributing noise source has a level of 51 dB - 0.97 dB = 50 dB

Figure 2.3 Finding the result of combined noise levels

Column 3 of figure 2.3 is the number of decibels subtracted from the total level to determine the actual contribution of a noise source. However, if the difference between the total noise level and ambient is less than 3 dB, the ambient level is to high to get an accurate reading and another method of finding the degree of contribution must be used.

A useful aspect of the decibel scale is a better approximation to our perception of relative loudness. This is because the ear reacts logarithmically to variations in sound pressure. However, the concept of loudness is very subjective and the decibel scale is not a precise model. We noticed above a 6 dB increase in sound pressure level results in a doubling of the actual sound pressure. But the ear doesn't recognize this as a doubling of loudness. It takes a full 10 dB increase in sound pressure level for us to consider the sound to have doubled in loudness; a 6 dB increase results in a discernible difference in loudness; while a 3 or 4 dB increase is barely perceptible.

Loudness is defined as the magnitude of the sensation of a sound and is a function of both the SPL and its spectral distribution. By this definition alone, one can perceive the subjective quality of loudness. Even so, loudness and loudness level have been quantified through the use of the phon and sone scales. The phon

scale measures loudness level. The loudness level of any sound is the median SPL, in decibels, of a pure 1000 Hz tone perceived to be as loud as the sound in question. The family of curves describing the contours of equal loudness level are known as the Fletcher-Munson curves and have been accepted by the International Standards Organization as ISO R-226. One problem with the concept of loudness level is it still follows a logarithmic distribution. Since it was thought an arithmetic distribution would make it easier to explain the concept of loudness to the layman, the sone scale was developed. A loudness [as opposed to loudness level] of one sone is defined as a tone of 1000 Hz that is 40 dB above the threshold of the listener. Since the sone scale is arithmetic, a loudness of two sones is twice as loud as one sone, a loudness of 15 sones is three times as loud as a loudnesss of 5 sones, etc. The relationship between loudness level and loudness is:

$$P=40+33.3\mathrm{Log}_{10}S$$

where: P=Loudness level in phons
S=Loudness in Sones

In everyday situations, it's rather obvious the apparent loudness of a noise source varies with the distance from the source. But to determine the magnitude of this variation, let's first consider a point source

radiating sound at 'P' watts of power uniformly in three dimensions. In this case, sound power denotes the total amount of sound energy radiated by a source per unit time. It is usually expressed in Joules per second, more commonly known as watts. This concept is analogous to the expression of the rate of flow of heat or electrical energy which is also expressed in watts. If we imagine a sphere of radius 'R' and surface area $4\pi R^2$ surrounding this point source, we can determine the amount of power being generated per unit area. This is called the intensity [I] of the sound and is mathematically described as:

$$I = P/4\pi R^2$$

It's clear the intensity of a sound source varies inversely with the square of the distance. This is known as the inverse square law. Now let's express sound intensity level in decibels by the relation:

$$IL = 10\log_{10}[I/I_o]$$

where: I_o = An internationally accepted reference standard of 10^{-12} W/m^2

To evaluate the change in Intensity Level in decibels between two points at distances R_1 and R_2 from the point source, we can simply take ten times the logarithm of the ratio of the two intensities. By letting $R_2 = 2R_1$, and by arbitrarily defining the SPL at distance R_1 as a reference level, we can write:

$$IL_c = 10\log_{10} \frac{P/4\pi[2R_1]^2}{P/4\pi R_1^2} = 10\log[.25] = -6 \text{ dB}$$

Thus, we can see that the intensity level of a sound source decreases by 6 dB with a doubling of distance. Conversely, it will increase by 6 dB with each halving of distance. The corresponding change in sound pressure level can be calculated in the same manner and with the same results. These are variations of the inverse square relationship and are valid only if the source qualifies as a point source.

A sound source may be considered a point source if the distance from the source is large in relation to the size of the source. We have just seen, for a point source, the sound intensity level and sound pressure level emanating from the source is inversely proportional to the distance from the source in accordance with the inverse square law. If, for a spherical source with radius 's', the inverse square relation holds true, and the product of the radius of the source and the wave number is much less than one, [$ks \ll 1$], then the source may be considered a point source. In this discussion of aircraft noise, the radial distances from the aircraft we are concerned with are measured in terms of miles. Under these circumstances, aircraft can be considered as point sources.

When detail is required in measuring sound pressure

levels, the sound source is analyzed in single or one-third octave bands. An octave, in this context, is the frequency interval between two frequencies having a ratio of 2:1. The first octave starts at 32.25 Hz and keeps doubling to 16,000 Hz; the highest practical and usable octave. A one-third octave band is the frequency interval between two frequencies with a ratio of 1.26:1. It's used when a single octave can't provide the degree of detail necessary for a sound spectrum analysis.

Sound, just as light, is subject to the phenomena of refraction. You have probably noticed the refraction of light while looking into a stream of clear water. The image of an object at the bottom of a stream appears closer to you than it actually is. This is due to the difference in the index of refraction. In other words, since water is more dense than air, the speed of light in water is somewhat slower than it is in air causing the light ray to bend toward you. This is why the object appear closer than it is. This phenomena obeys Huygen's principal and is illustrated in figure 2.4a. The same basic principle holds for sound. The speed of sound in air varies with temperature and humidity. The effects of humidity are very small and usually neglected, while an increase in temperature will cause an increase in the speed of sound. The speed of sound can be found by the relation:

$$C=[1.4P_o/D]^{1/2}$$

where: P_o=atmospheric pressure [varies with elevation and weather]

D=air density [varies as temperature and elevation]

Note the speed of sound varies as atmospheric pressure and density, which in turn are dependent upon elevation and temperature. A simpler expression relating the speed of sound to temperature only is:

$$c=48.99[T+459.67]^{1/2}$$

For most calculations, the speed of sound is assumed as 1130 fps at 72 °F. To see these effects in practice, consider figures 2.4b and 2.4c. The first illustration shows a stratified atmosphere with warm air layered on top of cooler air. As the sound travels up, it begins to speed up as it passes through warmer air. This causes it to bend, or refract, downward. In the second illustration, cool air is layered on top of warm air. In this case, sound will begin to slow as it passes through cooler air and refract upward.

Sometimes confused with refraction is the principle of diffraction. Diffraction is the deviation of a wave from a straight line. Again using light as an analogy, consider the shadow produced by a single point source of light as you hold your hand near a surface. The shadow is crisp with no ragged edges. But when you pull your hand away from the surface and closer to the light, the

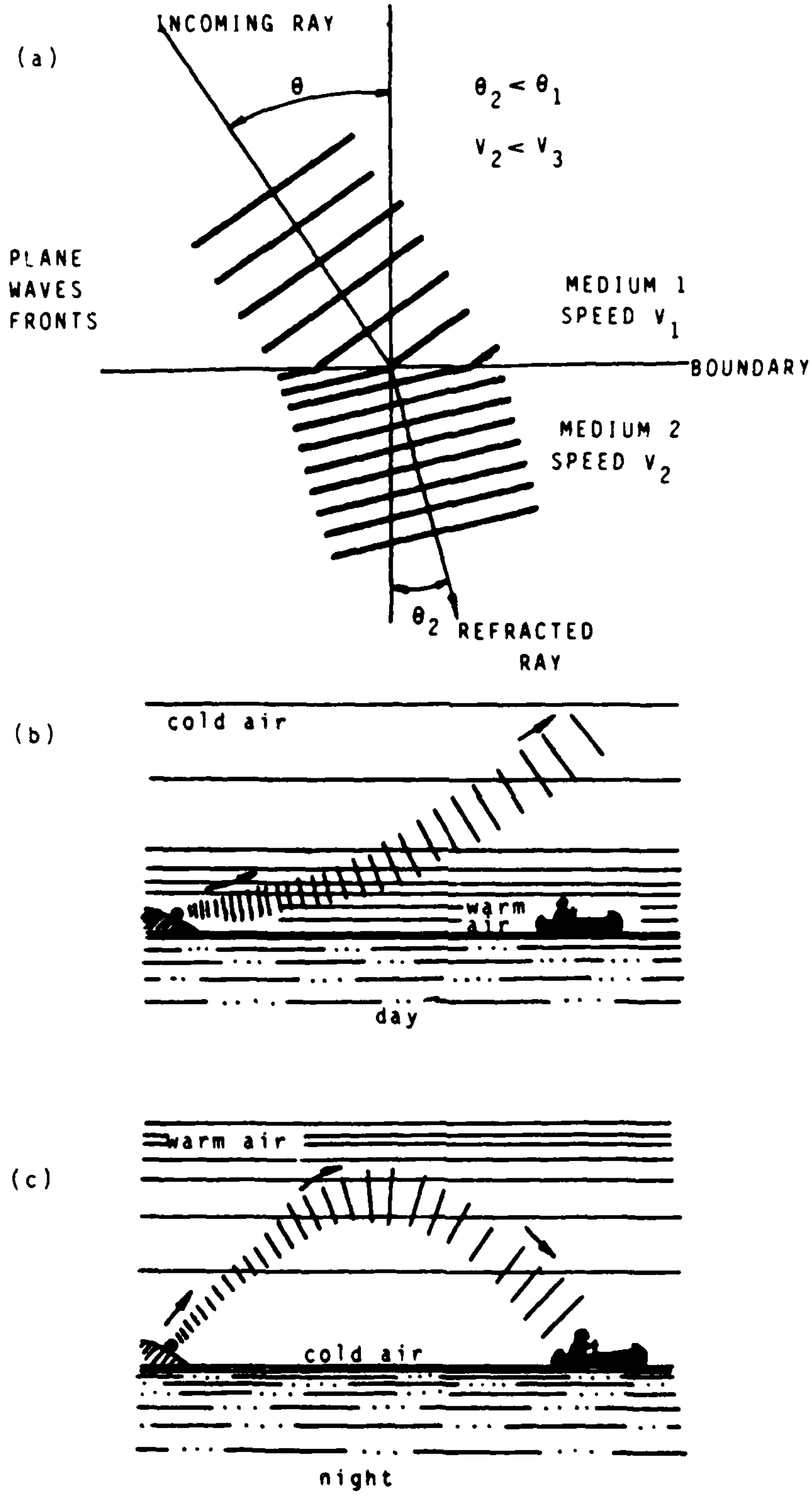


Figure 2.4 [a] Rays bend toward normal passing into dense medium [b] Refraction of sound passing from warm to cool air [c] Refraction of sound passing from cool to warm air

shadow becomes fuzzy. This is because the light has diffracted or bent around the edge of your hand. Diffraction of sound happens in the same manner. It is most apparent when passing through openings or traveling around objects. The amount of diffraction depends on the size of the opening or object in relation to the wavelength. As a wave front contacts a large object [relative to its wavelength], little sound will enter the region behind the object and a shadow region is formed. A small object will provide little obstruction and the sound will continue almost as if there was no interference. The passage of sound through an opening is similar. If the opening is small, a wave front striking the opening will be heavily diffracted. The waves emenating from the opening will take the form of a spherical wave. Thus the opening will act as a point source when transmitting the incident sound. These concepts are illustrated in figure 2.5.

2.2 AIRCRAFT NOISE

The vast majority of the noise generated from an airport is from jet aircraft [as opposed to propeller driven aircraft]. There are two principle sources of sound from a jet engine: exhaust noise and fan/compressor noise. The exhaust noise is a result of the high velocity exhaust gases passing through ambient air inducing a

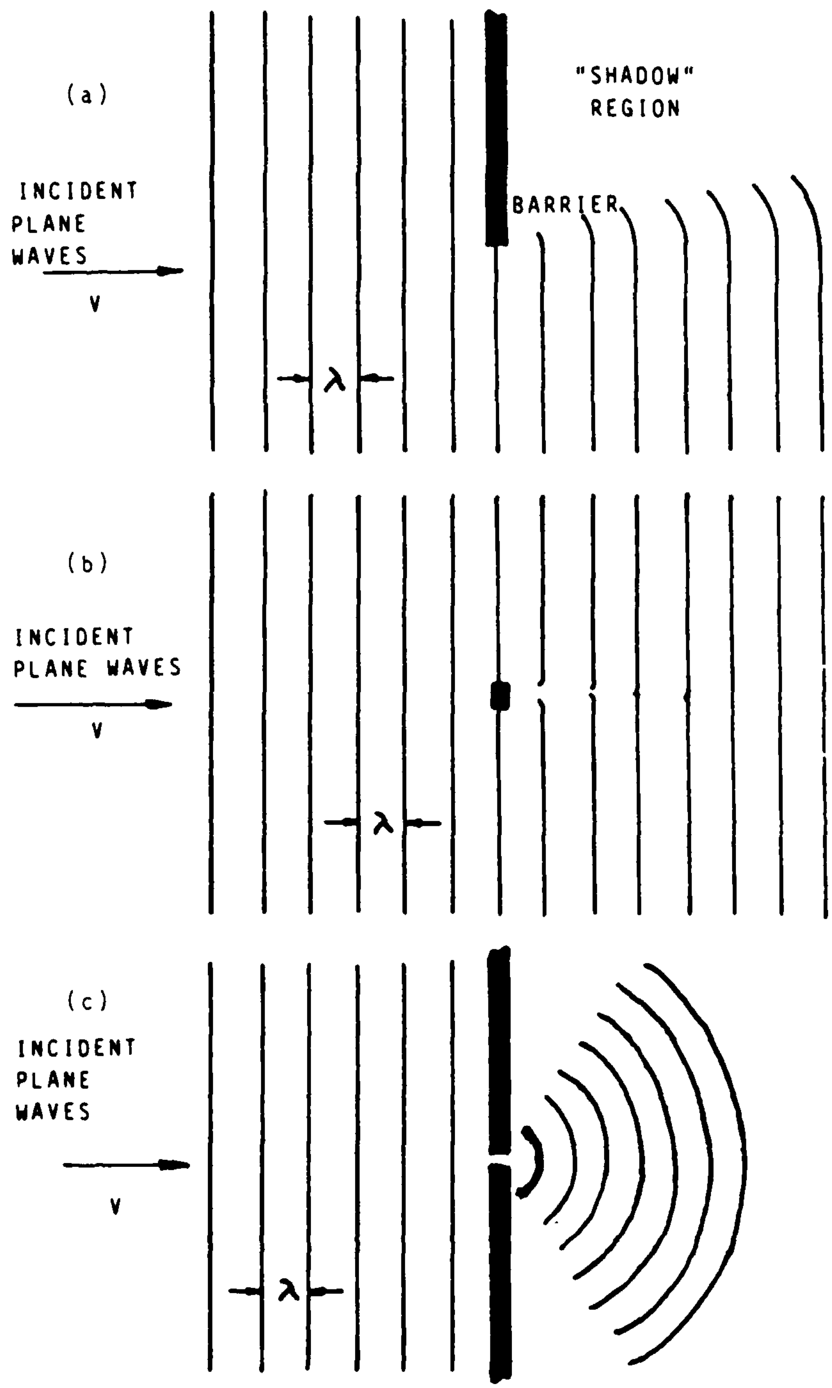


Figure 2.5 Diffraction of waves [a] around an object large compared to wavelength [b] around an object small compared to wavelength [c] through a small opening

large shear stress in the surrounding air. The resulting sound energy covers a wide range of frequencies. Exhaust noise increases after the passing of an aircraft and reaches a maximum at a point about 135° from the nose of the aircraft. Probably the most annoying sound from a jet engine is the high frequency whine or screech. This is a result of the turbo-machinery of the jet engine. These sounds may also cover a wide frequency range and usually contain high frequency pure tones; which are particularly annoying to the human ear.

Since an aircraft must use maximum thrust during takeoff, this is also when they are most noisy. The SPL of the noise heard depends on the source and the distance the observer is from the source. So it's important for a plane to reach as high an altitude as possible before it overflies a noise sensitive area. At certain airports, flight tracks may be adjusted to reduce the noise impact on surrounding communities. Another procedure is for the aircraft to cutback on power while overflying a sensitive area. However, this means the aircraft may expose areas further away from the runway to higher levels of noise. One begins to realize the importance of sound insulation to support the operational techniques of reducing the intrusion of aircraft noise.

Landing aircraft produce less noise because of the lesser power requirements. But the whine of the turbo-

machinery is still an annoying intrusion. Since aircraft descent typically begins 5 to 10 miles from the airport along a straight 3° glideslope, there is less of an opportunity to alter flight tracks to decrease the effects of this intrusion. Therefore, landing aircraft, although less noisy than those taking off, will increase sound levels on the ground, possibly affecting noise sensitive areas with little recourse for decrease through changes in operational technique. Again, this only strengthens the requirement for good acoustical design and construction techniques to provide an acceptable interior noise environment.

To define the affected areas and show the degree of impact, several noise metrics and the FAA integrated noise model [INM] were developed. These models are available to the general public in the form of noise contour maps. These maps prove a great tool for land use planning and noise impact assessments. These metrics and the INM are described next.

CHAPTER 3 THE NOISE METRICS

3.1 SINGLE EVENT MAXIMUM SOUND LEVEL METRICS

All acoustical metrics are comprised of three basic components: 1] sound pressure level in dB, 2] frequency or pitch, and 3] time. The sound pressure levels of various frequencies, determined for a given point in time, form a fingerprint of the sound. The A-weighted sound level is consistently used as the single event maximum sound level metric and is also used for noise certification of small propeller driven aircraft. It attenuates high and low frequency noise in accordance with the 40 phon equal loudness contour. This scale was originally developed to reflect the ear's response to low sound pressure levels, typically below 55 dB. But over the years,it's proven to correlate well to the response of the human ear. As a result, this network is used almost exclusively in all types of sound pressure level measurements. The B-weighted and C-weighted networks were developed at the same time as the A-weighted network. The B-weighted network also attenuates high and low frequency noise but does so following the 70 phon equal loudness contour. It was intended to approximate the ear's response at medium SPL's. The C-weighted network is essentially linear and was intended to approximate the ear's response at high SPL's. Extensive

field use proved the A-weighting more accurate than either the B- or C-weighting. The D- and N-weighted networks were developed for use in measuring aircraft noise. These networks are frequency-filtered to reduce the effects of low frequency noise and to recognize the increased annoyance levels associated with higher frequencies. The N-weighting is a direct approximation of the Perceived Noise Level [discussed next]. The D-weighting is the same as the N-weighting except at a level of 7 dB lower. It's found more frequently on sound level meters than the N-weighting and is used to approximate Perceived Noise Level by the following equation:

$$PNL=dB[D]+7$$

The A,B,C,D, and N weighted networks are tabulated in figure 3.1[b] and depicted graphically in figure 3.1[a]. Using these figures and an octave or one-third octave band analysis, the weighted or unweighted sound level of any source may be calculated. The available analysis may be weighted or unweighted. For example, the sound pressure levels listed in figure 2.2 are unweighted. To calculate the A-weighted SPL, algebraically add the A-weightings from figure 3.1[b] to the SPL of each octave band to obtain an A-weighted SPL by octave band. Add these levels logarithmically to obtain the overall A-weighted SPL.

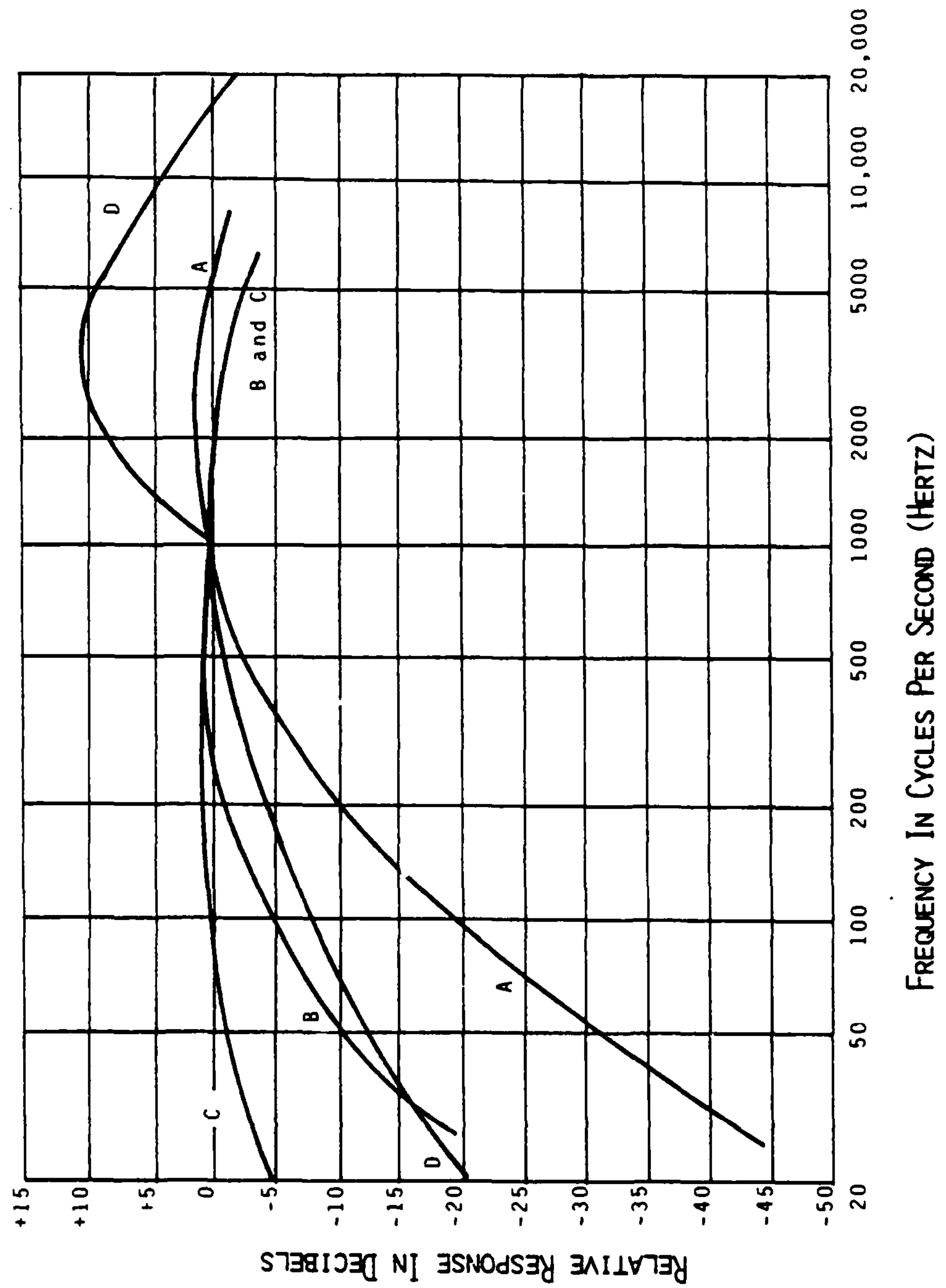


FIGURE 3.1(a) A graph of the A,B,C and D-weighted networks

f_c	A	B	C	D	N
25	-45	-20	-4	-19	-12
31.5	-39	-17	-3	-17	-10
40	-35	-14	-2	-15	-8
50	-30	-12	-1	-13	-6
63	-26	-9	-1	-11	-4
80	-23	-7	-1	-9	-2
100	-19	-6	0	-7	0
125	-16	-4	0	-6	1
160	-13	-3	0	-5	2
200	-11	-2	0	-3	4
250	-9	-1	0	-2	5
315	-7	-1	0	-1	6
400	-5	-1	0	-1	6
500	-3	0	0	0	7
630	-2	0	0	0	7
800	-1	0	0	0	7
1000	0	0	0	0	7
1250	1	0	0	2	9
1600	1	0	0	6	13
2000	1	0	0	8	15
2500	1	0	0	10	17
3150	1	0	-1	11	18
4000	1	-1	-1	11	18
5000	1	-1	-1	10	17
6300	0	-2	-2	9	16
8000	-1	-3	-3	6	13
10000	-3	-4	-4	3	10
12500	-4	-6	-6	0	7
16000	-7	-8	-9	-3	4
20000	-9	-11	-11	-5	2

FIGURE 3.1[b] The A,B,C,D, and N weightings for 1/3 octave bands

Although the A-weighted network correlates well with the human ear, it doesn't take into affect the annoyance level of aircraft noise. We are especially sensitive to sounds in the 500 Hz to 4000 Hz range. This phenomena was apparent in 1959 when Boeing introduced the 707-120. At the time, Boeing claimed jet aircraft were no more noisy than propeller-driven craft. This allegation was based on the fact the overall SPL's of the jet aircraft

and propeller-driven aircraft were identical. Yet people perceived the jet aircraft to be louder. The answer was in the spectral distribution of the two different sounds. The jet produced higher SPL's in the more annoying frequency range than the propeller-driven aircraft. This prompted K.D. Kryter to develop the perceived noise level [PNLdB] as a single number measure to relate the actual physical measure of noise to the subjective feelings of annoyance of that noise. Its evaluation requires an octave or one-third octave band analysis with instantaneous measurements of SPL's in the various bands at half-second intervals. These frequency intervals are weighted according to the amount of annoyance perceived using the subjectively derived noy scale. The noy scale rates the annoyance of a sound in noys as a function of frequency and sound pressure level. A standard noy table is provided in the appendix. The PNL of a band analysis is determined from the following equations.

$$PNL[k]=40.0+33.22\times Log_{10}[N_{[k]}], \quad PNdB$$

For an octave band analysis:

$$N[k]=0.7n_{[k]}+.3\Sigma n_{[i,k]}$$

For a one-third octave band analysis:

$$N_{[k]}=0.85n_{[k]}+.15\Sigma n_{[i,k]}$$

$n[i,k]$=perceived noisiness values in noys for the 'i'th octave band during the 'k'th time interval

$n_{[k]}$=largest of $n_{[i,k]}$ values

PNL can also be approximated with the relation:

$$PNL \approx dBA + 14$$

To get an idea of the difference between SPL's and PNL's, some common noises and their respective levels are tabulated in figure 3.2. A comparison of a jet airliner at takeoff with a propeller-driven aircraft at takeoff is shown in figure 3.3. Note the high SPL's in the high frequency range for the jet airliner vs. the Electra. This difference becomes very important when you realize the average human ear can tolerate low frequency noise about 30 db higher than high frequency noise. Using the procedure outlined in section 2.1, it's easy to verify the overall SPL of each aircraft at 104 dB. Using the noy table in appendix A, we find the sum of the noy indices for the jet airliner is 397 noys with a maximum of 93 noys. The Electra has a total noy value of 155 noys and a maximum of 42 noys. Using the above equation, this calculates to 115 PNdB and 102 PNdB respectively. The PNL scale readily indicates the obvious; jet aircraft are more annoying than propeller-driven aircraft. These values are used to develop PNL contour plots for an aircraft. An example of such a plot is shown in figure 3.4.

Since the PNL scale is based on the dB scale, an increase of 10 PNdB results in a doubling of the subjective sensation of noisiness. It also suggests an

Octave Band Spectrum Analysis of Various Noises

Source Octave Band	Jet at 1600'	Garbage Disposal at 3 Ft.	Vacuum Cleaner at 3 Ft.	Freight Train at 100 Ft.	Washing Machine at 3 Ft.	Truck at 20 Ft.	Refrigerator at 3 Ft.	Voice at 3 Ft.	Desert
63	97	73	68	92	60	80	45	40	50
125	98	78	72	91	61	79	46	53	37
250	97	80	75	89	60	77	45	62	30
500	96	81	75	87	59	72	44	64	24
1000	93	80	73	81	58	69	42	61	20
2000	89	78	71	73	57	62	40	57	18
4000	82	75	67	66	50	52	38	45	16
8000	75	69	62	56	48	40	35	30	15
SPL	104	87	81	96	67	84	52	68	50
Noys	125	52	33	61	12	25	3.5	11	0
PNdB	110	97	90	106	76	87	58	75	--

Figure 3.2 Comparison of SPL and PNL

EXAMPLE OF USE OF PERCEIVED NOISE LEVEL
FOR COMPARING NOISE FROM TWO TAKEOFFS

Octave bands of frequency in cycles per second	DATA MEASURED AT TAKEOFF			
	Commercial Jet		Electra	
	SPL	Noys	SPL	Noys
20-75	89	14	102	35
75-150	83	13	100	42
150-300	95	40	83	17
300-600	97	52	76	12
600-1200	99	60	77	13
1200-2400	98	93	74	19
2400-4800	95	93	65	12
4800-10000	84	32	56	4.7
Overall SPL	104 dB		104 dB	
Perceived Noise Level	115 dB		102 dB	

Figure 3.3 Comparison of the Sound Pressure Levels and Perceived Noise Levels of two aircraft

equivalent increase in overall SPL. This fact can be used to advantage in approximating sound insulation requirements for a building for programming purposes. If

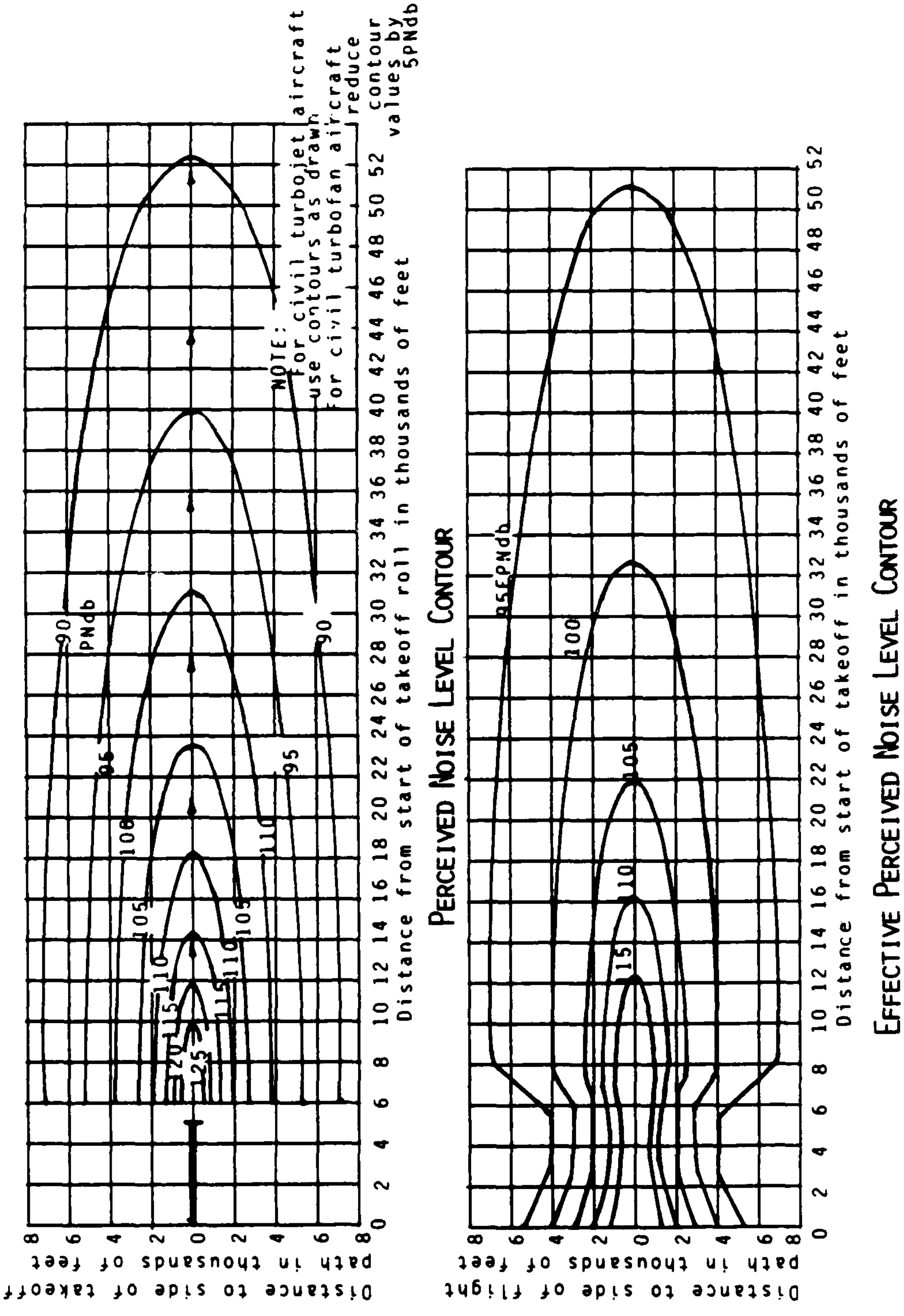


FIGURE 3.4 Examples of PNL and EPNL contour plots for a turbojet and turbofan at takeoff

a PNL contour plot is available, you can find the PNL at a building site. By knowing the desired interior level in dBA, use the above equation to express this interior level in PNL. The difference between this level and the exterior level in PNL will be the required transmission loss.

Since the human ear is sensitive to pure tones, corrections to account for this was applied to PNL resulting in the tone corrected perceived noise level [PNLT]. The procedure requires a one-third octave band spectrum analysis of a noise event for each one-half second of duration. Each band is checked, through an iterative process, to determine an effective SPL of the pure tone at each band if it exists. For frequencies below 500 Hz and above 5000 Hz, the applied correction is .17 dB per decibel of effective SPL the pure tone exceeds the actual SPL at that band. All other frequencies receive a correction of .34 dB per decibel effective SPL. The largest correction of all 24 one-third octave bands is the only correction added to the PNL to obtain the PNLT for the one-half second time interval. This process is repeated for each one-half second of duration and the results plotted as a PNLT curve representing the entire time-history of the event. This procedure is outlined in detail in FAR 36.

3.2 SINGLE EVENT ENERGY DOSE METRICS

During the studies of annoyance levels of aircraft noise, examiners noticed people rated flyovers of long duration as more annoying than those of short duration. This prompted the addition of a duration correction factor for the PNLT. The resulting annoyance rating is coined the effective perceived noise level [EPNL] and is mathematically described as:

$$EPNL=PNLTM+D$$

where: PNLTM=Maximum PNLT value over the duration of the event

D=duration correction factor

$$=10Log_{10}[\Sigma 10^{PNLT[k]/10}]-PNLTM-13$$

The duration of the event is based on the total time the aircraft is within 10 dB of maximum PNLT. Due to the considerations of pure tones and duration, EPNL can't be used effectively for determining sound insulation requirements for buildings. But it is considered a very accurate descriptor of the annoyance of aircraft noise. It's currently specified by Federal Aviation Regulation Part 36 [FAR 36] for use in certifying noise levels of foreign and domestic aircraft. The EPNL for a given aircraft is plotted to give a total noise footprint for the aircraft during takeoffs and landings. Examples of such plots are shown in figures 3.4 and 3.5. Plots of EPNL were used to develop the Noise Exposure Forecast, a cumulative energy average metric described in 3.4.2.

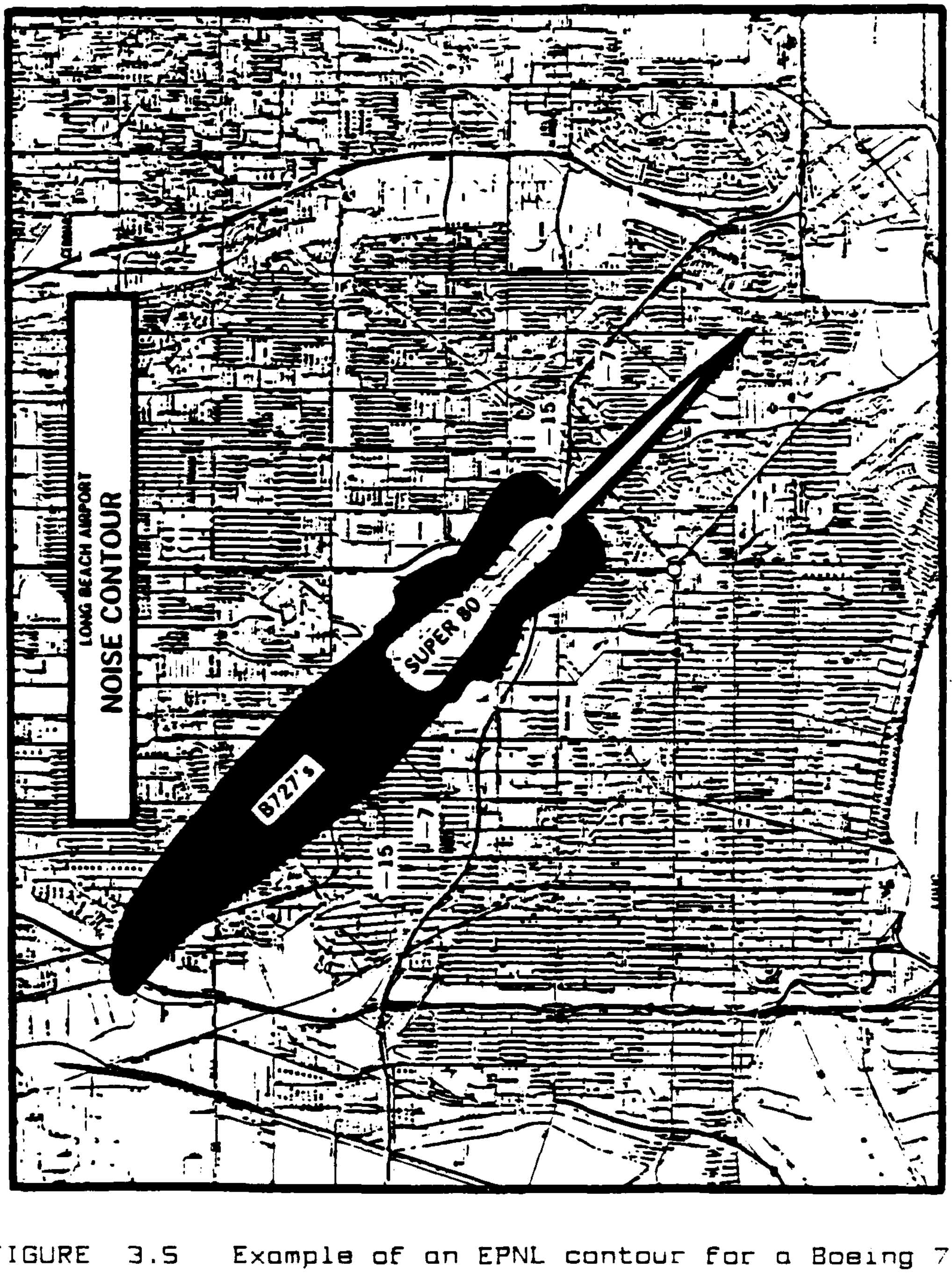


FIGURE 3.5 Example of an EPNL contour for a Boeing 727 and McDonald Douglas DC-9 at Long Beach Airport

Another single event energy dose metric in use today is the sound exposure level [SEL]. It was first developed in 1970 as the Single Event Noise Exposure Level [SENEL] and used to calculate the Community Noise Equivalent Level [CNEL] described in section 3.4.4. In 1972, the name was changed to SEL and it was adopted as the single event noise measure in developing the EPA proposed Day-Night Sound Level described in section 3.4.3. SEL is the A-weighted sound level of an event integrated over its duration and normalized to a reference duration of one second as illustrated in figure 3.6. The one second reference duration acts as a common denominator allowing the addition of several events of varying total durations. When calculating SEL, sufficient accuracy is obtained by defining duration as the time the event is within 10 dBA of its maximum A-weighted sound level. For SENEL, the threshold is 30 dBA. Mathematically defined:

$$SEL=10Log_{10}\ [1/t_0 \int_{t_1}^{t_2} 10^{dBA[t]/10}\ dt]$$

where: t_0=Reference duration of one second

t_1=Beginning of event

t_2=End of event

dBA[t]=Instantaneous SPL of event at time t

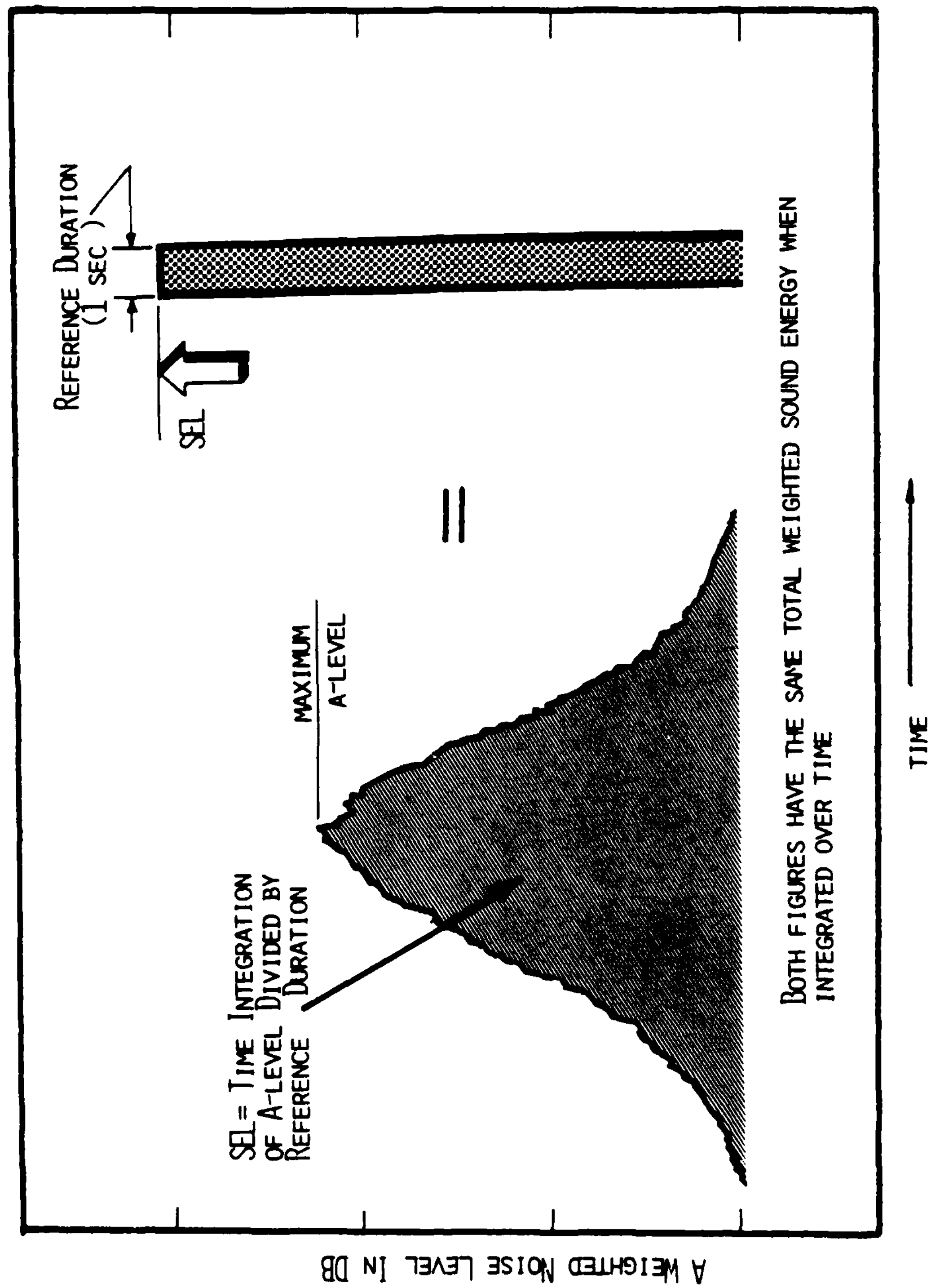


FIGURE 3.6 A graphic representation of the SEL concept

In practice, the integral sign is replaced by a summation sign and SEL is calculated at discrete intervals of one-half second or less.

Although the SEL calculation appears relatively easy, there are a multitude of variables to affect it. These variables are classed by: Aircraft type, Mode of operation, and Distance.

Aircraft type not only includes the model of aircraft, but also the type of engine installed. The main concern is takeoff thrust requirements since this affects the aircraft SEL. Aircraft type is only a partial determinant of the amount of thrust necessary for takeoff. Takeoff thrust also depends on the gross weight of the aircraft at takeoff. This, in turn, is dependent on the amount of cargo on board and the aircraft's stage length (length of trip). Stage length is important because it determines the amount of fuel the aircraft will carry, which affects aircraft weight and returns full circle to takeoff thrust requirements. Thus, aircraft type and stage length constitute the first two variables affecting SEL.

Mode of operation refers to takeoff and landing operations. SEL's for each of these conditions will depend on the takeoff and landing procedures at a specific airport. The most common procedures are: Standard Takeoff, Northwest Orient Airlines Noise

Abatement Takeoff, FAR 36 Takeoff, Standard Landing Approach, and the Two Segment Landing Approach. Additionally, certain airports may have their own procedures based on their developed community noise abatement program. Landing procedures are usually based on a 3° glideslope for large transports and a 4.5° glideslope for general aviation aircraft. The two Segment approach begins on a 6° glideslope and ends on a 3° glideslope. Again, this may vary with local noise abatement policies and must be reflected in the developed SEL charts.

Distance criteria depends on mode of operation. For landing, it's the distance along the ground track from the point of intersection of a line drawn from a land parcel of interest and perpendicular to the ground track to the landing threshold. For takeoff, it's the distance along the ground track from this same point to the brake release. Figure 3.7 graphically illustrates this concept.

All of this information must be considered while preparing a database of SEL charts. Fortunately, extensive studies have been done and the resulting database is readily available from the EPA [Ref. 14]. Figure 3.8 is an example of an SEL chart for the McDonald Douglas DC-10 and Lockheed L1011. Note the information in the upper right hand corner. These conditions are the

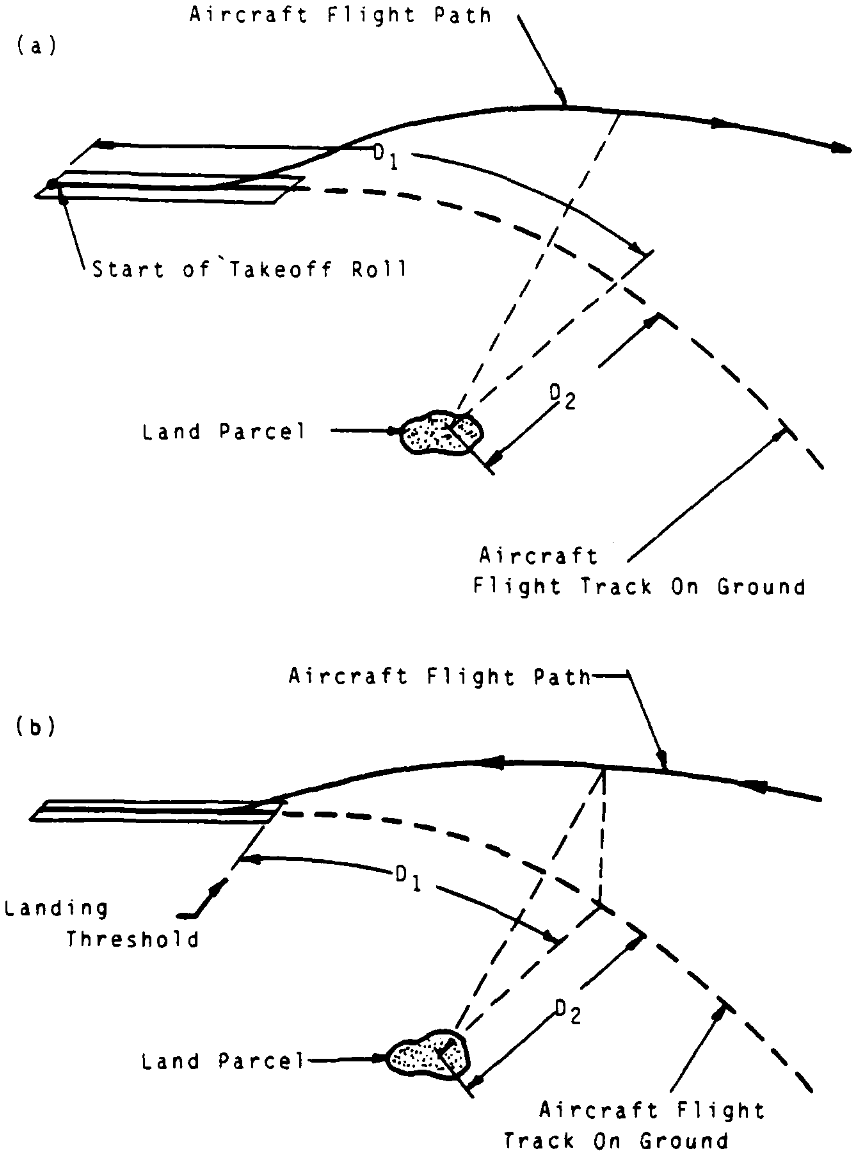


FIGURE 3.7 Distance criteria used in SEL and L_{dn} calculations

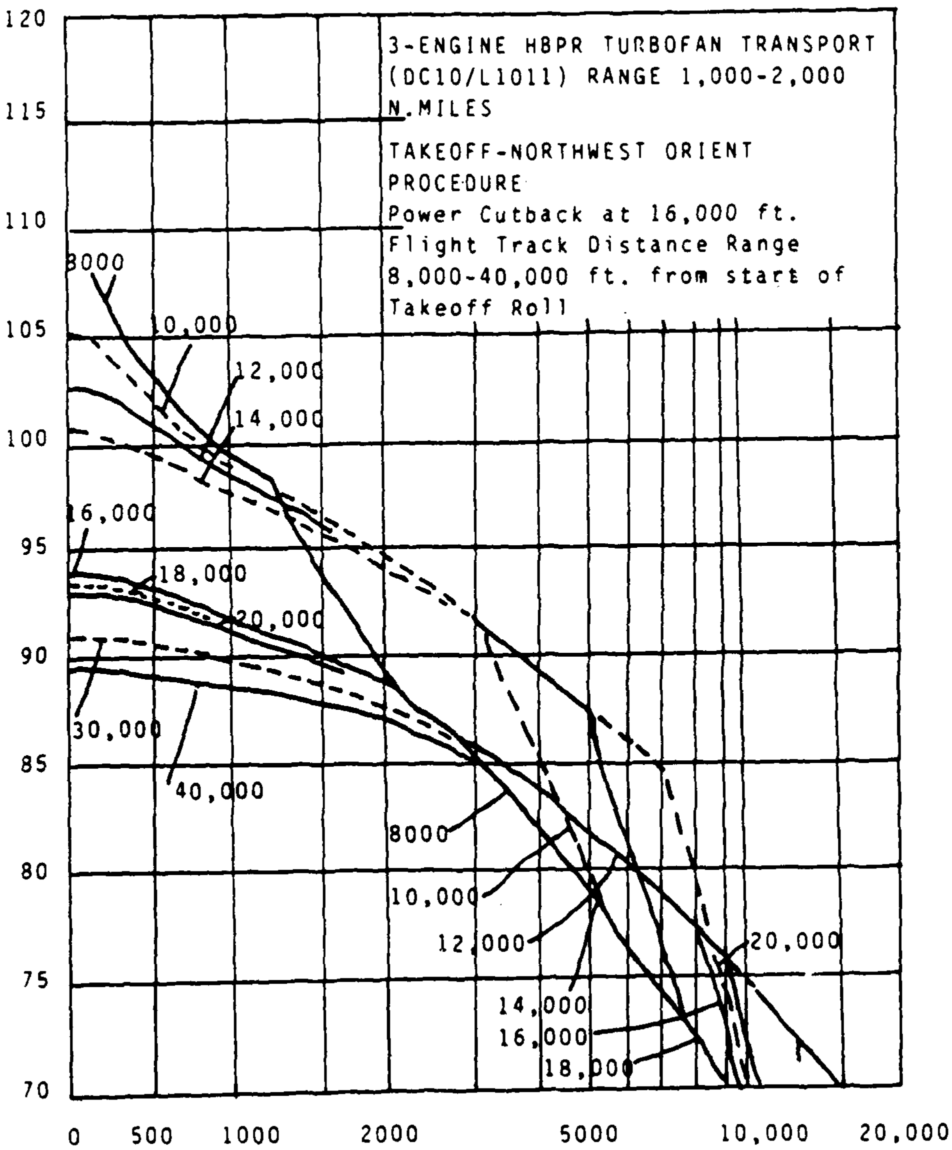


FIGURE 3.8[a] SEL chart for a McDonald Douglas DC-10 and a Lockheed L1011 at Takeoff

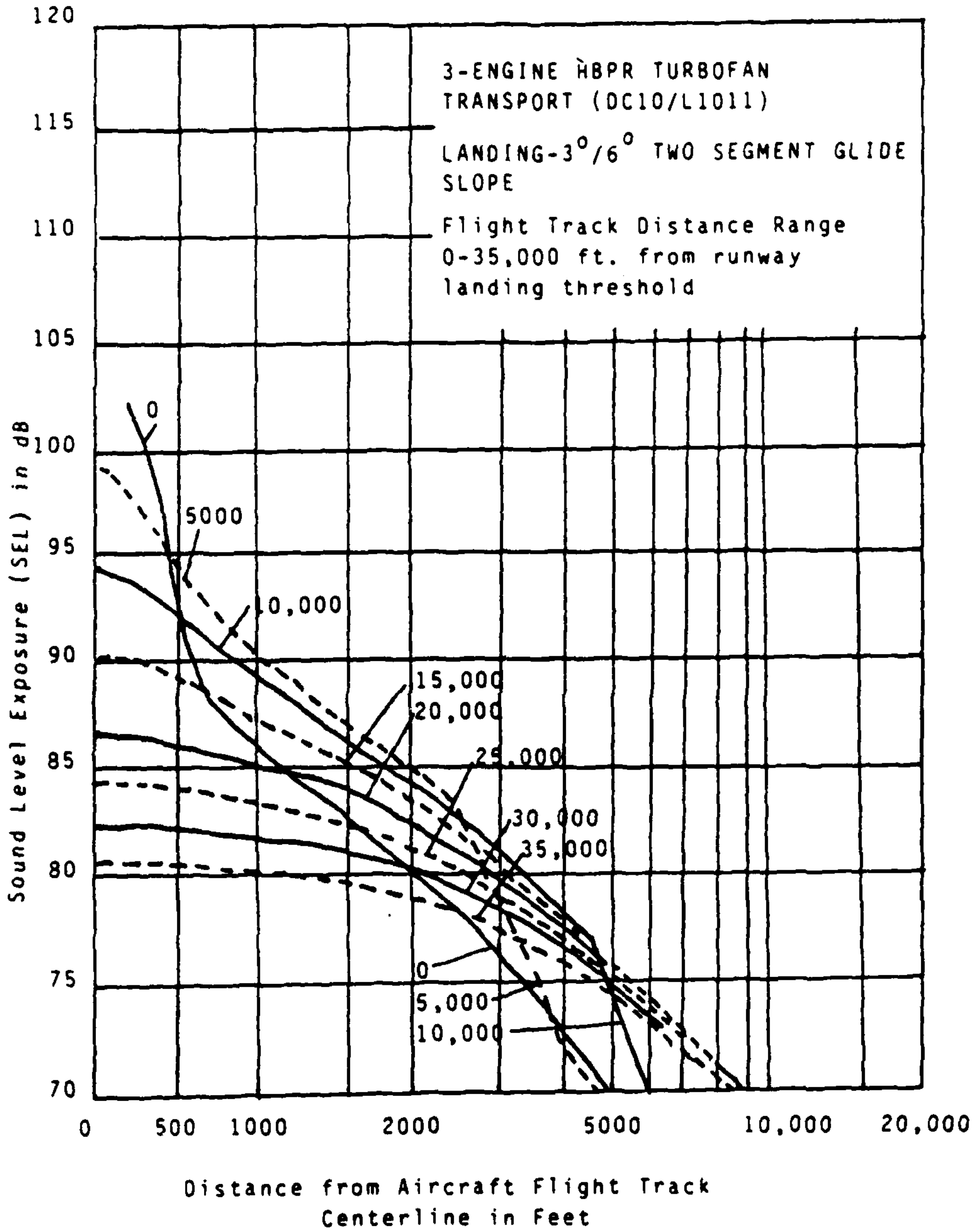


FIGURE 3.8(b) SEL chart for a McDonald Douglas DC-10 and a Lockheed L1011 while Landing

variables for which this chart is valid

Like the PNL metric, SEL can be tone corrected by replacing the dBA[t] value within the integral with the instantaneous tone corrected A-weighted sound level [dBAT[t]]. DBAT[t] is calculated according to ISO recommendation R507 or computed by:

$$dBAT=dBA+PNLT-PNL$$

3.3 CUMULATIVE TIME METRICS

The cumulative time metric was devised to provide a simple, easy to understand metric for presentation to the layman. This metric expresses the total amount of time a sound level in a particular environment exceeds a predetermined threshold. Due to their simplicity, their use grew until 1970. About this time, field studies indicated they didn't accurately assess the annoyance impact of aircraft noise, although they did possess several merits useful for determining sound insulation levels. None the less, they were never standardized and the computer models under development never completed. Even so, instruments intended to measure aircraft noise affects are still being produced today with the capability of measuring time-above. One of these metrics, the centile sound level, is still used by the Federal Highway Department in assessing the affects of traffic noise. For these reasons, this class of metrics

is described in detail.

3.3.1 CENTILE SOUND LEVELS

The centile sound descriptor [$L_{\%}$] is a statistical metric stating the percentage of time a certain sound threshold is exceeded. This rating was developed to reduce large amounts of data to a descriptive and manageable form, and to allow comparison of annoyance levels of various communities. Consider two strip-chart recordings of two areas within a community. Assume one indicates an ambient level of 60 dBA with frequent 5 dBA intrusions. If the second has an ambient level of 45 dBA and fewer intrusions, but peaking 20 dBA above ambient, a direct comparison of annoyance is difficult. But a statistical analysis stating percentage of time each area exceeds a threshold level simplifies the comparison.

The centile sound level is based on a free-flowing, continuously fluctuating noise source such as an equally spaced, constant flow of traffic. The number of events contributing to the overall noise level at a point is statistically represented as a Poisson distribution. But the rate of growth/decay of the noise level of an approaching/departing vehicle is an exponential function [Fig 3.9]. So it follows the centile levels will be exponentially distributed. Using this statistical method, one can analyze data obtained from an observation

period to determine centile levels. Another method is to record the sound levels on a strip-chart and manually construct a histogram to indicate what percentage of time the noise level is within a series of ranges; say at 5 dBA increments. Then it's a simple matter of adding the results of the histogram to determine cumulative levels; the centile levels. There are also sound measurement instruments available to do these calculations automatically. A standard observation period of one hour is typical to retrieve accurate results.

Still another method of estimating centile levels is discussed by Rettinger [Ref. 3] and rewritten here in brief. This method uses the basic principles of geometry and acoustics to develop a general relationship for estimating centile levels.

Referencing figure 3.9, assume an observer is a distance Y from an equally spaced constant flow of vehicular traffic. Since the vehicles are considered point sources, the inverse square law applies. Thus, the sound level contribution from a single vehicle at any point, a distance D from the observer, is the difference between the maximum sound level at distance Y and the inverse square attenuation due to the algebraic difference between D and Y. Since $D=[X^2+Y^2]^{1/2}$, the sound level heard by the observer, L_o, can be written as:

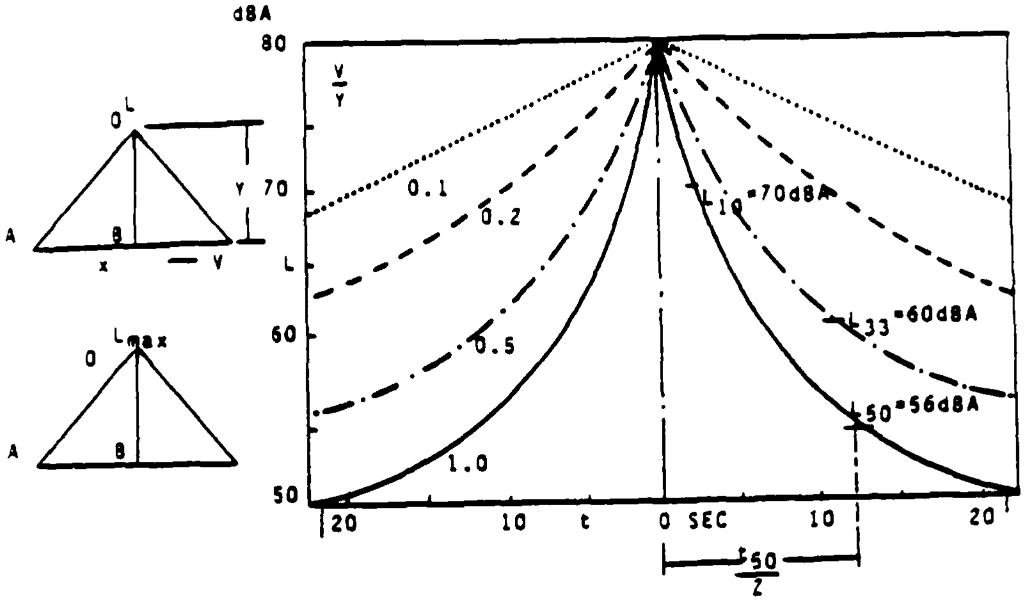


FIGURE 3.9 A typical plot of A-weighted sound pressure level vs. time for a vehicle passby

$$L = L_{max} - 20\mathrm{Log}_{10}\,\frac{D}{Y}$$

$$= L_{max} - 20\mathrm{Log}_{10}\,\frac{[X^2+Y^2]^{1/2}}{Y}$$

$$= L_{max} - 10\mathrm{Log}_{10}\,[1+[\frac{X}{Y}]^2]$$

By letting V represent vehicle speed in miles per hour, the distance X, in feet, can be defined as 1.467×V×t. By substitution:

$$L_f = L_{max} - 10\mathrm{Log}_{10}\,[1+ [\frac{1.467Vt}{Y}]^2]$$

During an observation period of one hour, L_f is exceeded for 3600f seconds. If N vehicles per hour exceed L_f, the duration of each event is t_f=3600f/N. The above equation

can be written in general terms as:

$$L_f = L_{max} - \Delta L$$

Since we're interested in developing ΔL, we're only concerned with the portion of the duration when the sound level rises from L_f to L_{max}. Assuming the vehicles at constant velocity, this will be $t_f/2$. Substituting, we have:

$$L_f = L_{max} - 10Log_{10}\ [1+[-\frac{1.467 \times V \times 3600f}{2YN}-]^2]$$

Simplifying:

$$L_f = L_{max} + 20Log_{10}N - 10Log_{10}[N^2 + 6.97 \times 10^6 [-\frac{fV}{Y}-]^2]$$

By substituting an appropriate value of 'f' [decimal value] into this equation, you will have a relation for that single L_f value. You can estimate 'N', the number of events exceeding L_f, from one of several statistical studies. The results of such a study are shown in figure 3.10. This table is part of the results of N. Olson's "Statistical Study of Traffic Noise" available from the National Research Council of Canada. Knowing the hourly traffic flow, use this table to estimate the number of passing vehicles at each sound output level [L_{max}]. This value of L_{max} is easily adjusted for inverse square attenuation at distances other than listed. Since this equation assumes all passing vehicles are identical, you must determine L_f for each group of vehicles with an identical sound output within each

AUTOMOBILE FLEET		TRUCK FLEET	
dBA at 50'	Fraction	dBA at 50'	Fraction
59	0.01	71	0.03
60	0.05	72	0.00
61	0.06	73	0.00
62	0.07	74	0.00
63	0.19	75	0.03
64	0.09	76	0.00
65	0.17	77	0.09
66	0.15	78	0.17
67	0.08	79	0.17
68	0.06	80	0.06
69	0.02	81	0.03
70	0.03	82	0.06
71	0.01	83	0.06
72	0.00	84	0.12
73	0.01	85	0.03
		86	0.03
		87	0.09
		88	0.03

FIGURE 3.10 Statistical results of SPL produced by two vehicle fleets

type class [e.g. Autos, trucks, etc.]. An energy summation of all L_f's at each sound output level will determine the partial L_f value for a given type class. After determining the partial L_f for each type class, a final energy summation will result in an estimate of the total L_f at the observation point. This process only provides an estimate. Actual levels can vary with vehicle mix and the actual numbers within a group of vehicles exceeding L_f.

Over the years, various centile levels have gained some significance. Some of these are listed below.

L_1≡Considered a maximum level of noise over a cumulative 36 seconds per hour. Ignores impulse noises with a combined duration less than 36 seconds per hour.

L_5≡Results in a broader assessment of noise levels than L_1

L_{10}≡Used as a measure of intrusiveness. This level has been used in American and English traffic regulations as the design limit for highway noise. The FHWA adopted L_{10}=60 dBA as the limit for highly noise sensitive areas.

L_{33}≡Originally used by HUD for land-use planning. L_{33}=65 dBA was the limit for outdoor noise.

L_{50}≡Median level of noise. Not an average sound level, but rather a level which outdoor noise exceeds as often as it doesn't.

L_{90}≡Considered ambient noise level.

L_{95}≡Sometimes used instead of L_{90}.

The centile rating has proven to correlate well with certain types of noise. The noise climate of a community is described well by stating the L_{10} and L_{90} centile levels [Some countries use L_5 and L_{95}, e.g. Australia]. It's also useful for assessing speech and sleep interference, a common complaint of excessive aircraft noise. Although the procedure described above could be easily applied to aircraft by developing a database similar to figure 3.10 for aircraft, it's proven inadequate as the basis for estimating aircraft noise and for developing related community noise regulations. This is because centile levels are calculated at discrete time intervals rather than being integrated over time. Thus they ignore noises of short duration--impulsive type noises. For example, Switzerland adopted the L_1 level as a criterion for measuring noise peaks. But this criterion will still ignore impulsive events of high magnitudes, even those potentially damaging to human health, for cumulative periods of up to 5 minutes in an 8 hour day. Since individual aircraft noise intrusions are of relatively short duration and infrequent occurence, this scale becomes unresponsive to such intrusions. Figure 3.11 is a graph of the L_2, L_4, and L_{33} centile ratings for aircraft durations of 10 seconds rising 60 dBA above ambient. Note the excessive number of intrusions necessary for these ratings to reflect them. As stated above, this rating works well with

situations such as free flowing traffic. As such, it may be possible to use this rating near a very busy international airport such as O'Hare or JFK. But most airports don't have the constant flow of traffic necessary to retrieve accurate results and to standardize this rating for aviation purposes. Therefore, its use has been limited to assessment of vehicular traffic noise.

3.3.2 TIME ABOVE METRICS

The centile rating defines the proportion of a time period exceeding a certain threshold. The inverse of the centile rating will give time, in minutes, a threshold level is exceeded. This is the basis of the time above metric. Since this class of metrics received a great deal of attention in the 1960's and early 1970's, the FAA developed the Aircraft Sound Description System [ASDS] as their basic technique for predicting community noise exposure from aircraft. The goal of the FAA was to provide an accurate, yet understandable system describing noise exposure to the community.

The basic product of ASDS is an exposure display stating the time, in minutes, noise levels exceed 85 dBA. In order to provide a method to compare results from differing situations, ASDS also provides a Situation Index. The Situation Index is a single number descriptor

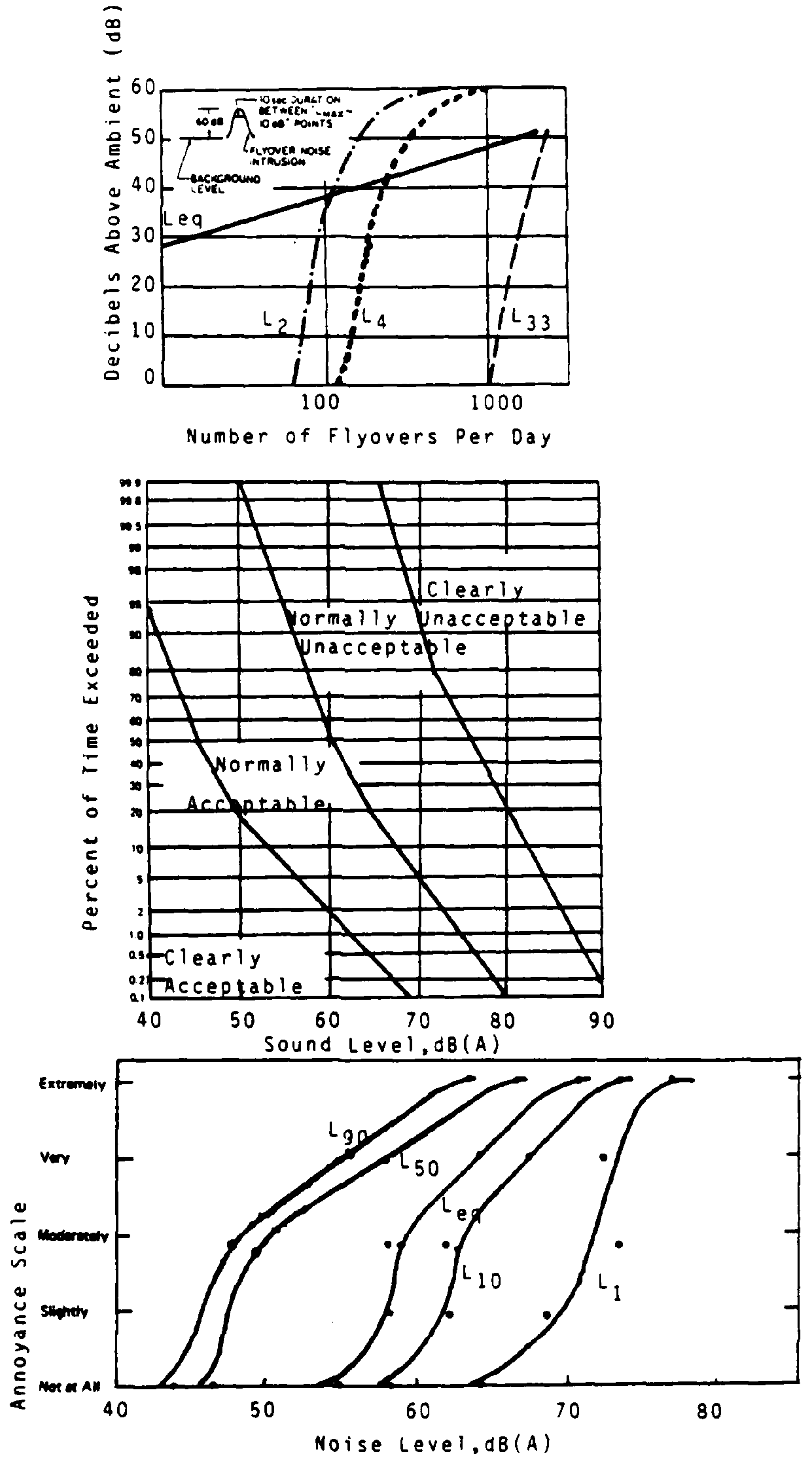


FIGURE 3.11 [a] Centile levels vs. aircraft flyovers
[b] Acceptable values of centile levels
[c] Centile level vs. community annoyance

calculated by integrating exposure time of a plot of land over its area. The result is a comparative measure of overall noise exposure expressed in acre-minutes.

ASDS was proposed with two different modes of calculation. Mode I is a simplified version suitable for calculation by hand. The required information is a map of the affected land area, location of runways and ground tracks, the number of operations by aircraft type, FAA calculation forms, and a database of 85 dBA contours.

The contour database is a computer generated table developed as a function of aircraft altitude and power setting. The result is corrected for excess ground attenuation and shielding by the aircraft fuselage. The contours are defined at 77°F, 70% RH, and no wind. The effects of pilot technique are also considered. Separate tables are required for individual aircraft at a variety of gross takeoff weights and the landing tables are based on a glideslope of 3°. Additional tables are compiled for aircraft with acoustic modifications, such as quiet nacelle engines. The final result is a table indicating distance of the contour edge from the ground track at a number of downrange distances. Aircraft altitude and cumulative contour area is given at each downrange distance.

Although the nine step calculation procedure for ASDS is relatively simple, it can be very tedious. The

following is brief summary of these steps.

Step 1: Record the operations data by aircraft type, gross weight, and number of takeoffs and landings.

Step 2: Select appropriate contours from the database.

Step 3: Draw the runway layout on a USGS topological map of the area.

Step 4: Add the ground tracks to the map.

Step 5: Match all aircraft operations with the appropriate ground track.

Step 6: Using an overlay, draw the appropriate contours about each ground track. The contours will be symmetrical about their centerline.

Step 7: The contours, when overlayed on one another, will create several zones of varying size and shapes. Number each zone sequentially. Theoretically, each zone will have varying degrees of exposure.

Step 8: Determine which contours overlap each zone.

Step 9: Calculate exposure time for each zone. Do this by determining the number of takeoffs and landings affecting each zone. Find total exposure by multiplying by the appropriate time constant (15 seconds per takeoff and 10 seconds per landing). To find a Situation Index, multiply the calculated exposure by the total area of each contour (obtained from database). An example of a simple ASDS contour map is provided in Figure 3.12.

There are two basic deficiencies to ASDS Mode I. First, this method assumes a constant 85 dBA exposure within a contour and zero exposure outside the contour. This is an obvious over simplification. With a dynamic noise source, and considering inverse square and atmospheric attenuation, the actual noise exposure within a contour is constantly changing. Second, peak noise levels at a site other than at the edge of a contour is undetermined. To correct these deficiencies. The FAA proposed ASDS Mode II-xx. Although Mode II-xx still assumed no exposure outside the contour, it did consider

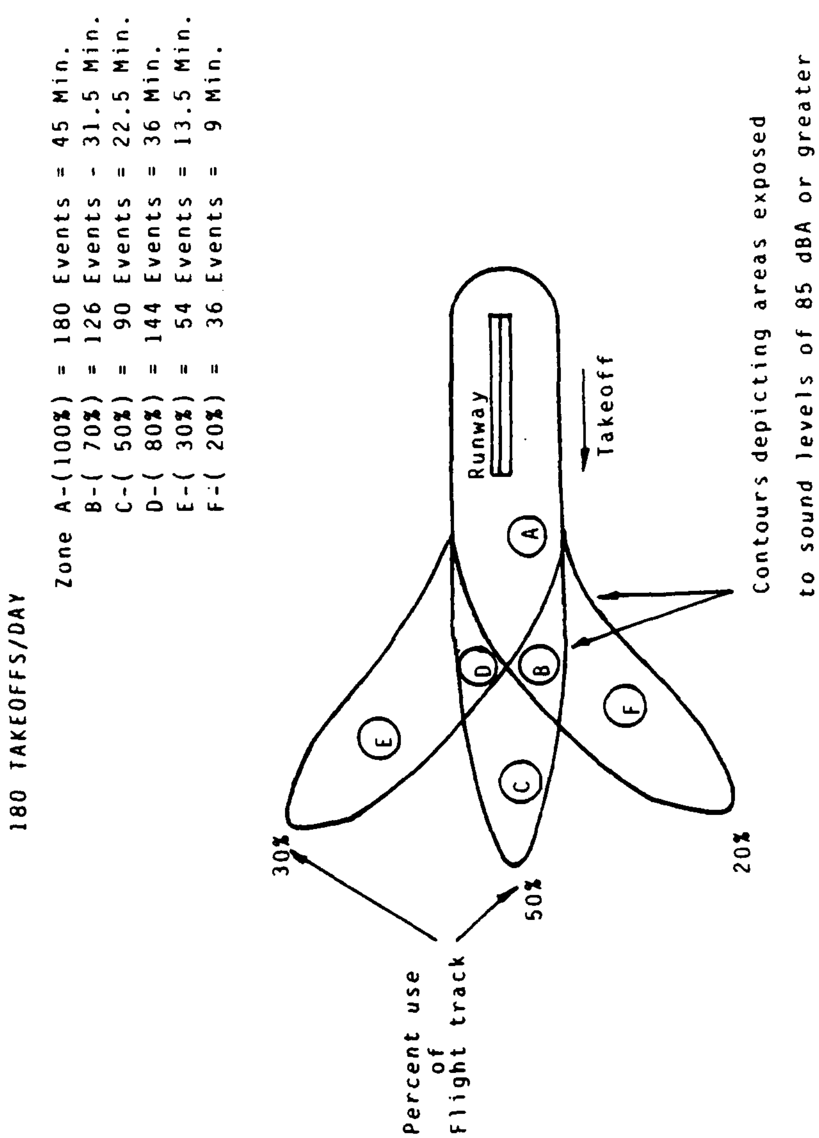


FIGURE 3.12 An example of a simple ASDS contour

the constantly varying noise levels within a contour. It also had the capability of determining time above any threshold. Thus, Mode II-90 determined the exposure time above a 90 dBA threshold. This allowed the determination of peak noise levels at any point within a contour. This information is ideal for determining building sound insulation requirements. Unfortunately, in relation to aircraft sound metrics, the time above metric had the same problems as the centile sound level described above. The FAA abandoned ASDS before Mode II-xx was ever fully developed.

3.4 CUMULATIVE ENERGY AVERAGE METRICS

The noise footprint of a specified aircraft, as may be developed from PNL or EPNL data, seems the ideal way to determine suitability of a site for construction. However, it doesn't consider annoyance levels caused by cumulative airport flight and ground operations, percentage use of various runways or flight tracks, or pilot operational techniques. For these reasons, the cumulative energy average metrics were developed. Cumulative energy average metrics are intended to define the average noise exposure of an individual over a given time period. The result of these metrics is a map of the airport, drawn to scale, with a set of contours indicating areas of land-use compatibility. It also

indicates those communities with potential noise problems and the degree of those problems.

The commonly used metrics today are the Noise Equivalent Level and the Day-Night Average Sound Level. These metrics are based on the cumulative A-weighted sound levels of a series of events, normalized to represent an average exposure. They were proposed by the EPA in 1972 in an effort to provide a standardized system for measuring all noises. Since the A-weighted scale is the basis of these measurements, they provide a convenient method of describing the total noise environment of a community.

This class of metrics went through many stages of development before we arrived at the current process. The first metric was the Composite Noise Rating. This metric was replaced by the more descriptive Noise Exposure Forecast, which, in turn was superceded by the DNL. These metrics are discussed in detail in the following pages.

<u>3.4.1 HISTORY OF DEVELOPMENT-THE COMPOSITE NOISE RATING</u>

This metric was first developed in 1952. It was used by military and civil air installations to predict community response to air operations. Initially, this response was based on the measurement of the noise spectrum of a single source. Thus, the first concept of

CNR resembled a single event maximum sound level rating, but normalized to predict community response to aircraft noise. In other words, the developed contours did not reflect the true SPL [or PNL as we'll discover later], but was a rather arbitrary selection. CNR was computed using the following eight step procedure.

1] First the SPL of the single noise source was quantified by overlaying a band spectrum analysis onto equal loudness contours. The noise was 'level ranked' to the nearest 5 dB. A 5 dB step is used because people seldom perceive changes in SPL of less than 5 dB.

2] A noise is perceived to be 5 dB higher if pure tones are present. Thus, a 5 dB correction is added to the level rank to account for presence of pure tones.

3] An intuitive correction of 5 dB was added to account for impulse noise. Since the definition of impulse noise was vague, the correction was optional and left to the interpreter of the system.

4] A repetitive correction was considered an

essential correction. A flyover was considered to be between 20 and 30 seconds in duration. The correction was based on the number of flyovers per unit of time. This correction was pulled from a precalculated table.

5] Background noise levels of a neighborhood were also considered important. Neighborhoods were described as; quiet suburban, suburban, residential urban, urban near some industry, and heavy industry. The corrections ranged from +5 dB to -15 dB in 5 dB increments.

6] Noncontinuous noise was allowed a 5 dB reduction if it occurred during the day. No corrections were applied to continuous noise or night time events.

7] A final correction was based on how well a community adapted to noise. It ranged from -5 dB to -10 dB. No correction was applied if the intruding noise was new. The -10 dB correction was reserved for emergency conditions or war time.

8] The final number was correlated to a

community response scale developed on the basis of 11 case histories. This scale attempted to predict:

No annoyance
Mild annoyance
Mild complaints
Strong complaints
Threats of legal action
Vigorous legal action

By 1957, the corrections for pure tones and impulse were eliminated. They were dropped because, with the exception of military aircraft, both qualities were virtually nonexistent in aircraft of that day. Also, the repetitive correction became a duration correction allowing the CNR to resemble a single event energy dose metric. The duration factor calculation resulted in the concept of an energy-weighted equivalent sound pressure level [L_{eq}, as described in detail in section 3.4.3]. Additional corrections were applied to the L_{eq}. Comprehensive studies developed these correction factors for noise levels of aircraft at various speeds, altitudes, and accelerations; their directivity patterns; and the atmospheric absorption of sound. Additionally, a wintertime correction of -5 dB was introduced if the noise occurred only during winter months. This resulted in contours that contained corrections for all elements thought to affect aircraft annoyance levels. The final modification in 1957 was reducing the annoyance scale to

five descriptors.

The most important change to CNR occurred in 1963 with the development of the perceived noise scale. This, coupled with a general dissatisfaction with the current system, prompted a total redevelopment of the CNR.

The redevelopment effort used the PNL noise descriptor, included findings from sociological surveys to date, and simplified calculations by excluding logarithmic addition for those not mathematically inclined. The first step was classifying aircraft by type, engine type, and performance. PNL contours described the noise contribution of each class while maintaining a 5 dB increment. To simplify calculations, the effects of duration were eliminated. It was assumed these effects were considered implicitly by the average duration of a flyover within a given distribution of the aircraft classes considered. The next change considered the number of a given aircraft using each flight track. These two factors were combined and the resulting numbers of operations broken into ranges, each range having a correction representing a 5 dB contribution in total energy. Previous studies showed the number of operations of a given type aircraft per flight track averaged between 10 and 30 operations from 0700 Hrs to 2200 Hrs. Using this fact, the correction was normalized so a zero dB correction resulted if this condition was

CNR	NEF	ESTIMATED COMMUNITY RESPONSES
<100	<30	ESSENTIALLY NO COMPLAINTS. HOWEVER, NOISE MAY INTERF RE OCCASIONALLY WITH CERTAIN ACTIVITIES.
>100 but <115	>30 but <40	INDIVIDUALS MAY COMPLAIN, PERHAPS VIGOROUSLY. CONCERTED GROUP ACTION IS POSSIBLE.
>115	>40	INDIVIDUAL REACTIONS WOULD LIKELY INCLUDE REPEATED, VIGOROUS COMPLAINTS, CONCERTED GROUP ACTION MIGHT BE EXPECTED.

FIGURE 3.13 EXPECTED COMMUNITY RESPONSE FOR CNR vs. NEF

present. Final modifications included a 10 dB penalty for night time operations [2200 to 0700] and eliminated corrections for community background noise. Based on case studies, the final CNR values were normalized to provide two border contours; CNR 100 and 115. The CNR is mathematically defined as:

CNR=110+[sum of all corrections] [PNdB]

Figure 3.13 is expected community response by CNR value.

Although the final procedure was used by both the military and civil communities in land use planning, there was a strong cry of dissatisfaction with the procedure by the civil aviation sector. The criticisms were threefold.

1] Since the noise contribution of each class of aircraft was taken to the nearest 5 dB, summing these contributions could result in gross over- or under-estimation of CNR values. This could prove disastrous if a land tract were said to fall outside a 100 dB contour, thus appearing compatible for residential development, but should be within a 115 dB contour, which is essentially noncompatible for residential development.

2] The use of 5 dB steps for summing both the effects of aircraft movement and runway use magnified or obscured differences in operations; depending on if the number of operations fell in the middle or near one of the boundaries of a particular range. For example, a change from 9 to 10 operations resulted in a 5 dB increase in CNR while a change from 10 to 30 operations resulted in no change in CNR.

3] The development of the EPNL concept was proving to be an accurate descriptor of aircraft noise. This made it desirable to use this scale to predict community reactions thus

rendering the CNR obsolete.

3.4.2 HISTORY OF DEVELOPMENT-THE NOISE EXPOSURE FORECAST

The major difference between the CNR and the Noise Exposure Forecast [NEF] was the use of the EPNL descriptor and the concept of continuous energy summation [as opposed to the 5 dB step function]. The same basic information required for CNR is also needed for NEF. NEF's are calculated by aircraft class for a given flight segment. A flight segment is defined as a portion of a flight track with a constant number of operations of a given class of aircraft. Due to the number of calculations, a computer is required. Input data for each pair of aircraft class and flight track segment included an octave band spectrum, time duration vs. slant distance function, tone correction, number of operations for day and night, altitude profile, and power level profile. The following set of equations were used to calculate NEF for the 'i'th aircraft class and the 'j'th flight segment.

$$NEF_{D[ij]} = EPNL + 10Log_{10}[N_{D[ij]}/20] - 75$$

$$NEF_{N[ij]} = EPNL + 10Log_{10}[N_{N[ij]}/1.2] - 75$$

$$NEF_{ij} = EPNL + 10Log_{10}[N_{D[ij]} + 16.67N_{N[ij]}] - 88$$

where: $N_{D[ij]} = \frac{n_{D[i]}\ P_{ij}}{100}$ and $N_{N[ij]} = \frac{n_{N[i]}\ P_{ij}}{100}$

P_{ij} = percent use of flight segment j by aircraft class i

n_i=Number of operations for aircraft class i for Day or Night

$$NEF_j = 10Log_{10} \sum_i Antilog[NEF_{ij}/10]$$

$$NEF = 10Log_{10} \sum_j Antilog[NEF_j/10]$$

In the CNR concept, CNR 100 and 115 defined the boundaries of noise sensitive areas. It was desired to maintain the same basic boundaries for NEF. A series of calculations determined NEF values of 30 and 40 compared favorably with CNR 100 and 115 respectively. This appears to negate the value of the NEF concept. But the real value of NEF was in the increased sensitivity and accuracy to changes in aircraft operations. Thus, NEF allowed the use of the boundaries established by CNR, but allowed airport planners to more accurately assess the community affects of changes in airport operations.

Under NEF, aircraft were classed in terms of similar noise characteristics and takeoff/landing profiles. Each class was assigned a representative noise spectrum at a reference 1000 ft. Referencing figure 3.14, we can calculate an NEF at a point 'P' along a flight track and a distance 'y' perpendicular to the flight track. Altitude 'z' is calculated from known profile information. Knowing 'y' and 'z', the slant distance 'd' is determined. PNL's are calculated from the reference noise contour and corrected for inverse square attenuation and atmospheric absorption along distance

'd'. Corrections for tone and duration yield the necessary EPNL data. The NEF for a particular class of aircraft is calculated from this adjusted EPNL by correcting for frequency of operations using the above formulas. An energy summation for all classes and operations yields an NEF value as a function of input data and NEF distance 'y'. But to plot a contour, NEF distance must be determined as a function of NEF value.

The final step, shown graphically in Figure 3.14, is an iteration to develop this relation. The dashed line is the curve we need to construct while the solid horizontal line is the NEF value we wish to locate. Two arbitrary points of distance y_1 and y_2 are selected and the NEF determined from the above procedure. These points are plotted and a line is drawn through them to intersect the horizontal. A new distance, y_3 is determined and the process repeated. This continues until the difference between two successive iterations becomes 'sufficiently' small. The last trial is the perpendicular distance at which the NEF in question occurs. This process is repeated at 2000 ft. intervals along the flight track and yields the information necessary to construct NEF contours about the airport.

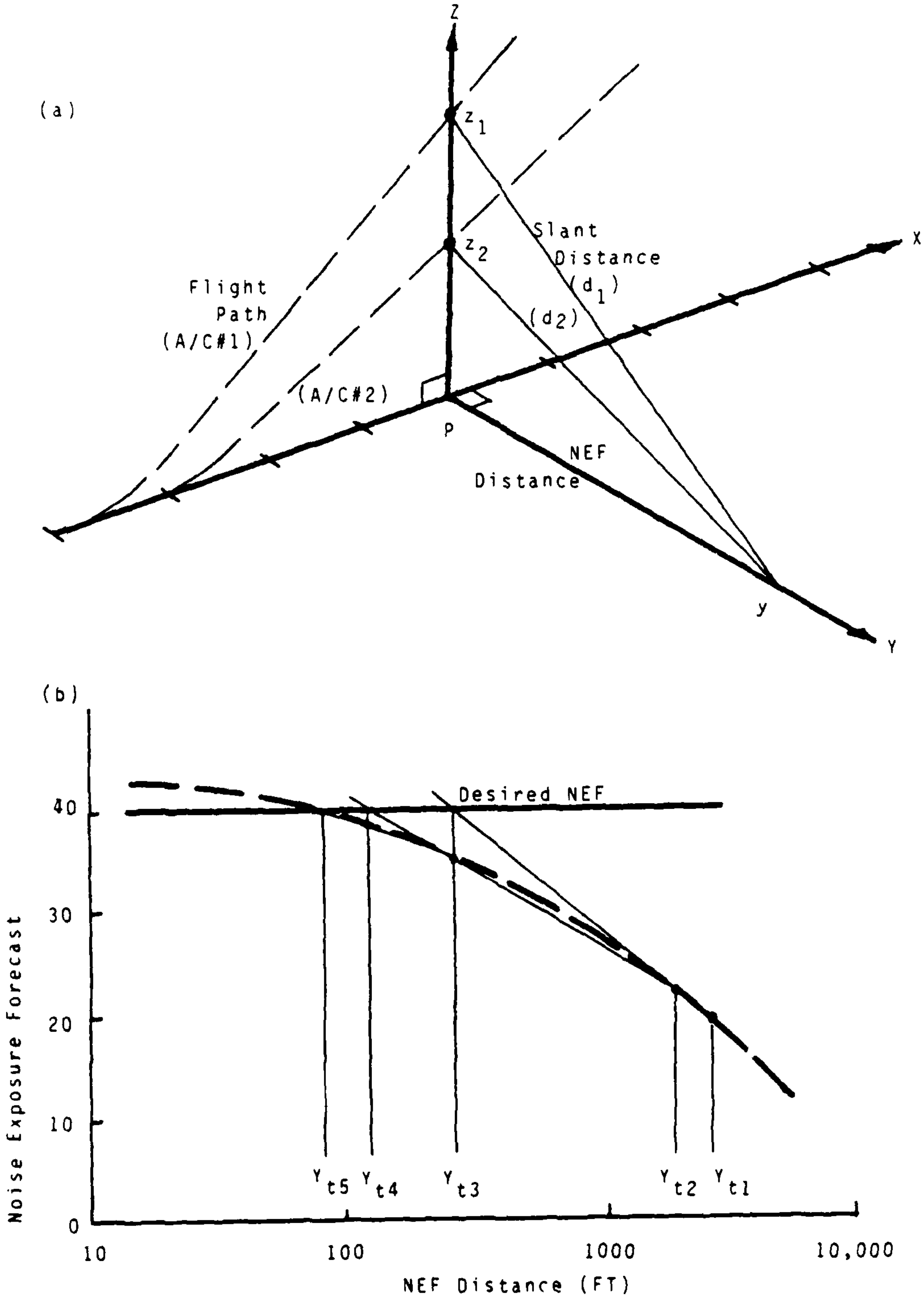


FIGURE 3.14 (a) Distance criteria for calculating NEF
(b) Graphic determination of NEF distance vs. NEF value

3.4.3 CUMULATIVE ENERGY METRICS-EQUIVALENT NOISE LEVEL

The Noise Equivalent Level [L_{eq}] is the basis for many of the noise metrics in use today. It was proposed by EPA as a descriptor useful for purposes other than assessment of aircraft noise. It is a simple but accurate noise descriptor capable of being measured with hand-held instruments. It's useful in virtually all situations and, most importantly, correlates well with known effects of noise on a community. Unlike the centile noise levels, this measure will consider impulsive noises no matter how short the duration.

Defined, L_{eq} is an equivalent constant sound level having the same amount of acoustic energy as the original sound source over the same time duration. It is mathematically defined as:

$$SEL = 10 \mathrm{Log}_{10} [1/T \int_{t_1}^{t_2} 10^{dBA[t]/10} \, dt]$$

where: $T = t_2 - t_1$
= Duration of event

t_1 = Start of event

t_2 = End of event

dBA[t] = Instantaneous sound pressure level of event at time t

Note if $T = [t_2 - t_1]$ = one second, the above equation results in SEL. This is because SEL is actually a special application of the more general L_{eq}.

In practice, it's common to divide the observation

period into discrete intervals of sound pressure levels: say 5 dB ranges. The time the noise level is within these ranges is a fraction of the total observation period, 'f'. Replacing the integral sign with a summation sign to account for discrete intervals, the above equation is rewritten as:

$$L_{eq}=10Log_{10}[\Sigma f_i 10^{L_i/10}]$$

One of the objectives of L_{eq} was to provide a simple method of calculating noise exposure. The following is a procedure to do so using only a sound level meter. Although not required, a graphic strip chart recorder compatible with the sound level meter being used will simplify data collection and reduce the possibility of error due to fatigue. The procedure described assumes a properly calibrated meter set to the A-weighted scale and 'fast' response. Figure 3.15 is an example of an actual measurement.

1] Using a data form similar to figure 3.15, record the SPL at 5 to 10 second intervals. The time interval required will depend on the nature of the sound. Rapidly fluctuating sounds require a short interval. A shorter interval also results in better accuracy. However, using short intervals for sounds with fairly constant levels only increases the

number of calculations without significantly increasing accuracy.

2) The number of samples collected affects calculational accuracy. In many cases, you may need only 100 data points for sufficient accuracy. To become accustomed in determining the number of samples required for accurate results, it may be desirable to initially obtain 400 to 500 samples. Analyze the first 100 samples to obtain a value of L_{eq}. Repeat the analysis but this time add a group of 50 to 100 samples to the original sample group. Recalculate the L_{eq} and compare the two results. If there is a significant difference, repeat the procedure until the results stabalize. The number of samples used in the final calculation is the number of samples necessary for accurate results in subsequent studies of similar noise environments.

3) After field measurements are complete, begin analysis by dividing the data into decibel ranges. Although 5 dB increments should be sufficient, the example in figure 3.15 used 1 dB increments. Find the midpoint of each interval by taking an

arithmetic average of the upper and lower bounds. Record th_ number of counts per interval. In figure 3.15, if the interval were 5 dB, the first interval would have 6 counts and a midpoint of 97.5 dB. We'll soon see the difference between using a 5 dB interval vs. a 1 dB interval is negligible in this case.

4] Find the fraction of the observation period each sound level occurs by dividing counts per interval by total number of counts in the observation period. Enter this in column 5.

5] Calculate $10^{L_i/10}$. Enter in column 6.

6] Multiply column 6 by column 5 and enter in column 7.

7] Determine a partial L_{eq} for each decibel range by taking ten times the logarithm of the number in column 7.

8] Using figure 2.3 or the equation for decibel addition in section 2.1, determine total L_{eq}. If figure 3.15 was divided into 5 dB intervals, the result would be 88.6 dB, a

negligible difference.

As a point of interest, this data lends itself well to determining centile sound levels. Using the data in column 5, sum the total percentage of time the noise levels are above a certain SPL. For example, by summing the total percentage of time the SPL is above 90 dB, we find 90 dB is the approximate value of L_{10}.

(1) SPL dBA	(2) Counts per dB	(3) Midpoint of SPL Interval	(4) Counts per Interval	(5) Time Fraction	(6) $10^{L/10}$ ($\times 10^7$)	(7) $f \times 10^{L/10}$ ($\times 10^5$)	(8) Partial L_{eq}
100		100			1000		
99		99			794		
98	1	98	1	0.005	631	316	75.0
97	2	97	2	0.010	501	501	77.0
96		96			398		
95	3	95	3	0.015	316	474	76.8
94	5	94	5	0.025	251	628	78.0
93	3	93	3	0.015	200	299	74.8
92	1	92	1	0.005	158	792	69.0
91	5	91	5	0.025	126	315	75.0
90	8	90	8	0.040	100	400	76.0
89	18	89	18	0.090	79.4	715	78.5
88	24	88	24	0.120	63.1	757	78.2
87	26	87	26	0.130	50.1	652	78.1
86	21	86	21	0.105	39.8	418	76.2
85	17	85	17	0.005	31.6	269	74.3
84	22	84	22	0.110	25.1	276	74.4
83	20	83	20	0.100	20.0	200	73.0
82	12	82	12	0.060	15.8	95.1	69.8
81	8	81	8	0.040	12.6	50.4	67.0
80	2	80	2	0.010	10.0	10.0	60.0
79		79			7.94		
78	1	78	1	0.005	6.31	3.15	55.0
77	1	77	1	0.005	5.01	2.51	54.0
76		76			3.98		
75		75			3.16		
		Total counts=200					L_{eq}=88.1

Figure 3.15 Calculation of L_{eq}

3.4.4 CUMULATIVE ENERGY METRICS-DAY/NIGHT AVERAGE LEVEL

In 1972, EPA proposed the day-night average sound level [L_{dn}, sometimes referred to as DNL]. This method is an effort by EPA to provide a national uniform standard of noise assessment. It is not unique to representing aircraft noise. It's intent is to measure all types of noise so as to provide an assessment of the total noise environment within a community with aircraft noise being but one facet. thus, it doesn't account for the annoyance effects of pure tones and impulse noise as did the CNR and the NEF assessments. In its simplest form, L_{dn} is a 24 hr L_{eq} with a 10 dB penalty applied to nighttime events. Nighttime is defined from 2201 hrs to 0700 hrs. Typically, L_{dn} values are determined on both a daily and yearly basis. The Yearly Day-Night Average Level [L_{dny}] is simply a logarithmic summation of the daily values. It is the yearly values that are plotted as contours on a map of the airport to indicate the impact of airport operations on a community.

Realizing the daily L_{dn} is a modification of the 24 hr L_{eq}, it can be mathematically defined as:

$$L_{dn} = 10\log_{10}\left[\frac{1}{86400}\left[\int 10^{\frac{dBA(t)}{10}} + 10\int 10^{\frac{dBA(t)}{10}}\right]\right]$$

The limits of integration on the first integral are from 0700 hrs to 2200 hrs expressed in seconds. The limits on the second integral are from 2200 hrs to 0700 hrs

expressed in seconds. The 86400 is the number of seconds in a day. Since this equation can become quite cumbersome for manual calculations, we would like to simplify it so some of the previous measures we've developed can be put to use. Notice the individual integrals are definitions of SEL. Since SEL curves are readily available, it would be convenient to rewrite this equation in terms of SEL. SEL curves are presented as a function of distance along a given ground track for a particular class of aircraft. Therefore, an equation expressed in terms of SEL will result in a partial L_{dn} by aircraft class and ground track which could be summed on an energy basis to arrive at the total daily L_{dn}. By introducing a new variable, N_{ij}, representing the number of aircraft from the 'i'th aircraft class using the 'j'th ground track, we can rewrite the above equation as:

$$L_{dn}=10Log_{10}[N_{D_{ij}}\times[\int 10^{\frac{dBA(t)}{10}}+10N_{N_{ij}}\times\int 10^{\frac{dBA(t)}{10}}]+10Log_{10}[\frac{1}{86400}]$$

By simplifying the logarithmic product into a logarithmic sum, we now have:

$$L_{dn_{ij}}=SEL_{ij}+10Log_{10}[N_{D_{ij}}+10N_{N_{ij}}]-49.37$$

Replacing everything to the right of SEL_{ij} with the variable K_{ij}, we now have:

$$L_{dn_{ij}}=SEL_{ij}-K_{ij}$$

This equation proves to be a much more manageable form for manual calculations. The value of K_{ij} can either be calculated by hand or picked off the graph in figure 3.16. Since the result of this equation will be a partial L_{dn} resulting from the 'i'th aircraft class following the 'j'th ground track, the total L_{dn} is calculated by:

$$L_{dny} = 10 \log_{10} \frac{1}{365} \sum_{i}^{365} 10^{\frac{L_{dn_{ij}}}{10}}$$

For a typical airport, the data necessary to develop a set of contours is so extensive it is impractical to do so by manual calculations. The necessary data is collected and input into a computer to develop the contours. These contours are available for use and review by anyone who has the need for them. However, there may be times when one may wish to manually determine the L_{dn} for a parcel of land. The following is a procedure to do so.

The first step is to collect all airport and aircraft operational data. This will be the same basic information required for NEF and CNR. Most, if not all, of this information is available from the airport manager or the airport tower personnel. It includes:

1] the orientation and length of the runways

and location of the ground tracks.

2] the perpendicular distance from the land parcel to the ground track and the distance along the ground track from this perpendicular to the brake release and landing threshold [Figure 3.7]. Ground tracks will vary with aircraft type.

3] the number of each type of aircraft contributing to the noise climate. If the number of jet operations exceed 5% of the total number of operations, propeller aircraft need not be considered.

4] the total number of takeoffs and landings by aircraft type. For more accurate results, break the takeoff operations down by stage length.

5] the number of operations by aircraft type for day and night.

6] the number of operations by aircraft type per ground track. A simple approximation is to assume the percent use of each ground track is

the same for each aircraft type. Now find the percent use of each track for all operations and use this to determine the number of each aircraft type using each ground track.

7] any special takeoff and landing procedures. See section 3.2.

After all the data has been collected and compiled, the partial L_{dn} values can be calculated. Start by locating the proper SEL curves for each type aircraft. These curves may also be available from the local airport authority or obtained from the EPA. Either calculate the value of K_{ij} or look it up in figure 3.16. The partial L_{dn} is the difference between these two values. The total L_{dn} is the logarithmic summation of all partial L_{dn}'s.

HUD has developed a simplified procedure for determining the approximate location of L_{dn} contours. This procedure should not be used for final determinations of land use compatibility. However, it is a convenient and satisfactory method for use during conceptual design stages. You'll still need to find the location of the ground tracks affecting the location in question as well as the number of daytime and nighttime flights. First, draw the appropriate ground tracks on a map of the airport. Now determine the effective number

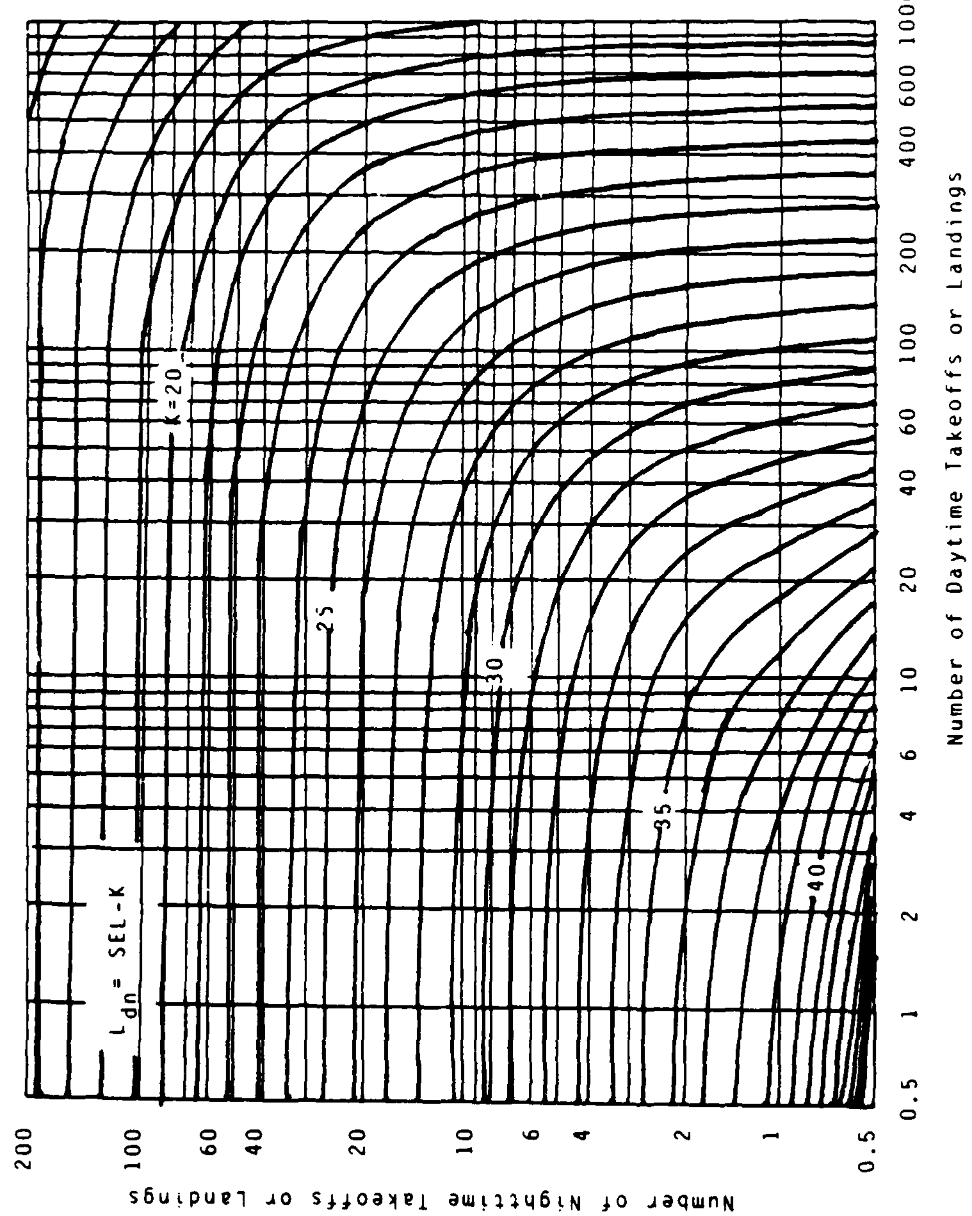
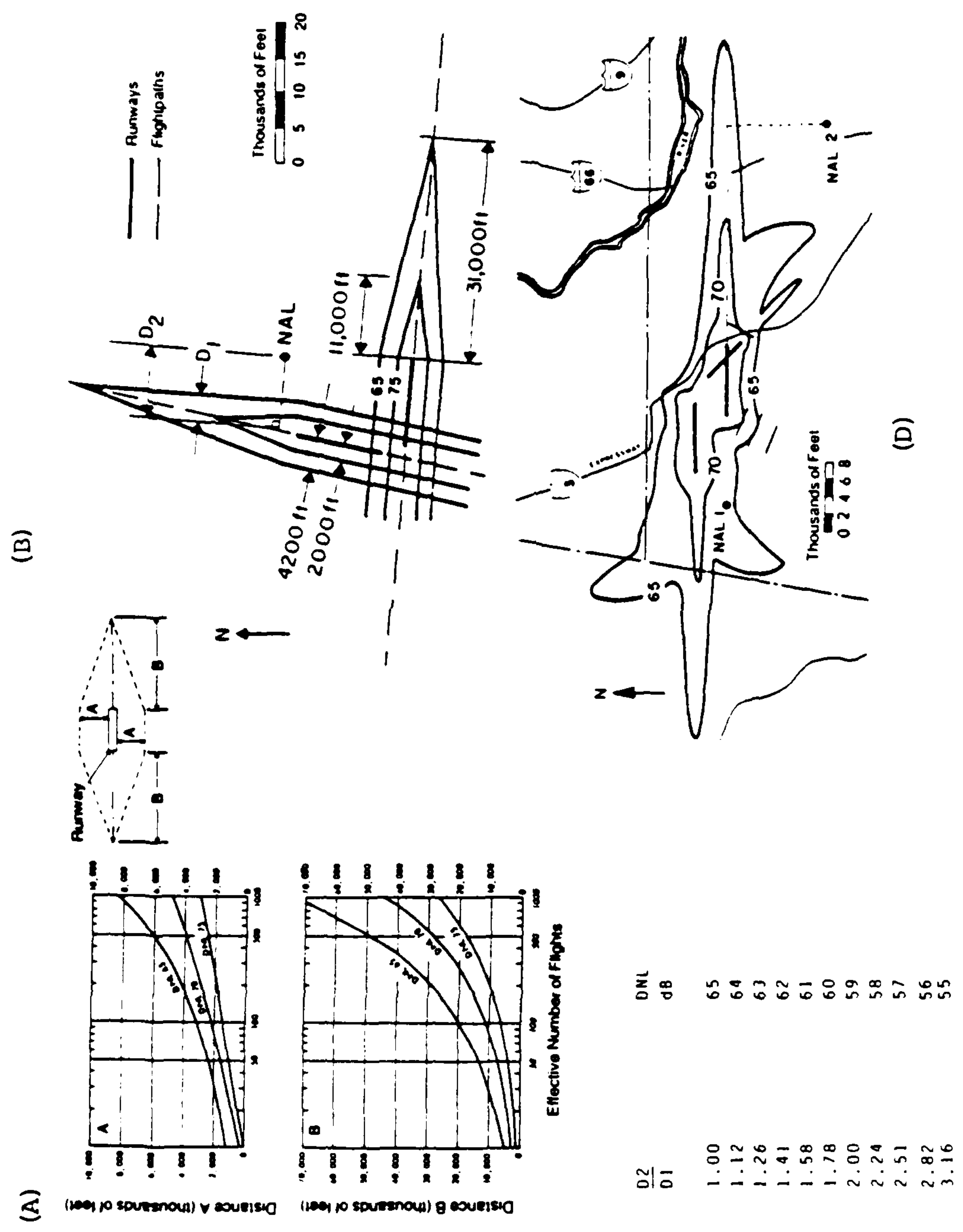


FIGURE 3.16 A graph to find the correction to be subtracted from SEL to determine L_{dn}

of flights by adding the number of daytime operations to 10 times the number of night time operations. Using the graphs in Figure 3.17[a], determine the distances A and B. Sketch the appropriate contours. Figure 3.17[b] is an example of the estimated contours for an airport with 225 effective operations.

L_{dn} values are also roughly interpolative. That is, if a noise assessment location [NAL] lies 500 ft from the 65 L_{dn} contour and 2000 ft from the 70 L_{dn} contour, then the L_{dn} at this location will be 65+[500/2500][70-65]=66 dB. But what if an NAL lies outside the 65 dB contour? HUD has developed a simple procedure for estimating the L_{dn} at such a location. First, find the distance from the location in question to the center of the flight path [D2] and to the edge of the 65 L_{dn} contour [D1]. Calculate the ratio D2/D1. Using the table in Figure 3.17[c], read the estimated L_{dn}. Obviously, these two procedures are based on the computer generated contour maps for the airport. Before making a final determination of the compatibility of this land parcel, ascertain if the maps you're using include the noise effects of traffic and other dominant noise sources. FAR 150 does allow airports to include these effects, but it is at the option of the airport manager. If the airport authority has developed their program to demonstrate only the effects of airport operations, you



D2/D1	DNL dB
1.00	65
1.12	64
1.26	63
1.41	62
1.58	61
1.78	60
2.00	59
2.24	58
2.51	57
2.82	56
3.16	55

FIGURE 3.17 HUD method for estimating L_{dn} contours

must determine the contribution of traffic noise yourself in order to make a final determination of compatibility.

Typically, the L_{dn} 65, 70, and 75 contours are all that's required for the contour map. Additional contours can be determined if desired. All land outside the 65 L_{dn} contour is compatible for all uses. Land parcels within 65 to 70 L_{dn} are normally incompatible with residential development. Areas between 70 and 75 L_{dn} are definitely incompatible for residential use but may be used for other purposes. Land parcels above 75 L_{dn} are discouraged for any use. Many city and municipal airports make an attempt to purchase all land exposed to 75 L_{dn} and above to ensure no problems will arise in the future. Figure 3.18 is a list of suggested land uses as determined by FAA. However, FAR 150 makes it very clear these are only suggested uses. Determinations of actual land use compatibility are the responsibility of the local community based on their needs and desires.

3.4.5 CUMULATIVE ENERGY METRICS-COMMUNITY NOISE EXPOSURE

The Community Noise Exposure Level [CNEL] was developed in 1970. This measure is used by the State of California and is the same basic measure as the Day-Night Average Sound Level. The difference is it uses SENEL instead of SEL [see section 3.2] and applies an additional 5 dB penalty for evening operations. It is

LAND USE COMPATIBILITY WITH DAY-NIGHT AVERAGE LEVELS

	YEARLY DNL IN DECIBELS					
LAND USE	<65	65-70	70-75	75-80	80-85	>85
Residential	Y	N[1]	N[1]	N	N	N
Mobile Homes	Y	N	N	N	N	N
Transient Lodge	Y	N[1]	N[1]	N[1]	N	N
Schools	Y	N[1]	N[1]	N	N	N
Hospitals	Y	25	30	N	N	N
Churches	Y	25	30	N	N	N
Concert Halls	Y	25	30	N	N	N
Gvnmt Services	Y	Y	25	30	N	N
Transportation	Y	Y	Y[2]	Y[3]	Y[4]	Y[4]
Parking	Y	Y	Y[2]	Y[3]	Y[4]	N
Business Offices	Y	Y	25	30	N	N
Wholesale/Retail	Y	Y	Y[2]	Y[3]	Y[4]	N
Photo/Optical	Y	Y	25	30	N	N
Agriculture	Y	Y[6]	Y[7]	Y[8]	Y[8]	Y[8]
Livestock	Y	Y[6]	Y[7]	N	N	N
Mining/Fishing	Y	Y	Y	Y	Y	Y
Outdoor Sports	Y	Y[5]	Y[5]	N	N	N
Outdoor Music	Y	N	N	N	N	N
Zoos	Y	Y	N	N	N	N
Parks/Resorts	Y	Y	Y	N	N	N
Golf/Stables	Y	Y	25	30	N	N
Water Recreation	Y	Y	25	30	N	N

NOTES:

[1] Noise level reductions [NLR] of 25 to 30 required

[2] NLR of 25 necessary where the public is received, office areas, noise sensitive areas, or where the normal noise level is low.

[3] NLR of 30 necessary where the public is received, office areas, noise sensitive areas, or where the normal noise level is low.

[4] NLR of 35 necessary where the public is received, office areas, noise sensitive areas, or where the normal noise level is low.

[5] Compatible with special sound reinforcement

[6] Residential buildings require an NLR of 25

[7] Residential buildings require an NLR of 30

[8] Residential buildings not permitted

25,30,35-NLR of 25, 30, or 35 required for compatibility

Figure 3.18 Land use compatibility by Day-Night Level

mathematically defined as:

$$CNEL = SENEL + 10Log_{10}[N_d + 5N_e + 10N_n] - 49.37$$

where: N_d=Number of flights from 0700 hrs to 1900 hrs

N_e=Number of flights from 1900 hrs to 2200 hrs

N_n=Number of flights from 2200 hrs to 0700 hrs

Statistically, the difference between CNEL and L_{dn} was found to be only .8 dB. For this reason, and to maintain a true national standard, CNEL will likely be replaced by L_{dn} within the next few years.

3.5 THE INTEGRATED NOISE MODEL

The integrated noise model [INM] was developed by the FAA as its computer-based noise-simulation model for describing impact of aircraft noise on the community. It provides a cumulative noise impact rating based on the Noise Exposure Forecast, Sound Equivalent Level, Day-Night Average Sound Level, or Community Noise Equivalent Level as described above. It also has the capability of providing a Time Above Threshold rating. These ratings are provided for a 24 hr day or for time periods between 0700 hrs and 2200 hrs, and between 2200 hrs and 0700 hrs. The database consists of separate noise files for each aircraft. There are user options available to make changes to these files as necessary. Program outputs include a listing of input data, a contour plot of the airport, and a table of computed noise values. An example printout is provided in

figure 3.19.

The INM is available to anyone who may have the need for this type of information. Some of the uses of the INM are:

1] Development of local land use controls and compatibility planning

2] Comparison of different classes of aircraft for purposes of scheduling to reduce the overall noise impact

3] Comparison of various operational procedures as part of a noise abatement program

4] Use in environmental impact statements

5] Assessment of proposed changes in airport operations

6] Determination of effective sites for airport acoustic barriers

The INM is available through various time-sharing vendors. It is also available through the FAA on a loan basis.

FEDERAL AVIATION ADMINISTRATION INTEGRATES NOISE MODEL 1.2
THIS IS A TEST OF MULTIPLE POINT GRID OUTPUT

INTER-SECTION	OFF SET	PERIOD	65	75	85	95	105	115	Leq	Ldn	NEF	CNEL
0,B		24 HOUR	65.3	31.2	13.4	4.4	.0	.0	71.9	75.1	39.1	75.6
		EVENING	9.4	4.5	2.0	.7	.0	.0				
		NIGHT	8.3	3.8	1.5	.5	.0	.0				
1,B		24 HOUR	67.4	35.3	14.1	4.0	.0	.0	71.2	74.4	38.4	74.9
		EVENING	9.5	5.1	2.2	.6	.0	.0				
		NIGHT	8.5	4.3	1.5	.4	.0	.0				
0,C		24 HOUR	67.5	33.3	13.1	.0	.0	.0	66.4	69.7	33.1	70.1
		EVENING	9.8	4.9	2.0	.0	.0	.0				
		NIGHT	8.5	4.1	1.5	.0	.0	.0				
1,C		24 HOUR	70.7	34.2	13.6	1.3	.0	.0	69.3	72.4	36.4	73.0
		EVENING	10.0	5.0	2.1	.2	.0	.0				
		NIGHT	8.9	4.1	1.6	.1	.0	.0				
0,D		24 HOUR	68.2	31.7	10.3	.1	.0	.0	65.1	68.4	32.0	68.8
		EVENING	9.8	4.6	1.3	.0	.0	.0				
		NIGHT	8.5	3.9	1.3	.0	.0	.0				
1,D		24 HOUR	68.8	30.3	9.8	.9	.0	.0	70.8	73.9	38.8	74.5
		EVENING	9.9	4.4	1.3	.2	.0	.0				
		NIGHT	8.7	3.6	1.3	.1	.0	.0				
0,E		24 HOUR	65.8	29.9	5.0	.4	.0	.0	66.6	69.8	34.0	70.3
		EVENING	9.4	4.4	.7	.1	.0	.0				
		NIGHT	8.3	3.6	.7	.0	.0	.0				
1,E		24 HOUR	66.7	29	4.8	1.2	.1	0	73.5	76.6	42.8	77.3
		EVENING	9.5	4.2	.7	.2	0	0				
		NIGHT	8.4	3.5	.6	.1	0	0				
0,F		24 HOUR	59.5	27.5	4.0	1.1	.1	.0	69.4	72.7	38.3	73.4
		EVENING	8.5	4.1	.6	.2	.0	.0				
		NIGHT	7.4	3.4	.5	.1	.0	.0				
1,F		24 HOUR	62.7	28.8	4.0	.6	.0	.0	67.4	70.6	35.3	71.2
		EVENING	8.9	4.2	.6	.1	.0	.0				
		NIGHT	7.8	3.6	.5	.1	.0	.0				

X-START	Y-START	X-STEP	Y-STEP	NX	NX	OPTIONS
0.00	1000.00	1000.	1000.	2	5	*******

FIGURE 3.19 An example printout from the Integrated Noise Model

CHAPTER 4 CONCLUSION

Through this review of the multitude of metrics available to measure the effects of aircraft noise, one can surmise the subject of noise measurement is an extremely complex one. Over the years, researchers have continually refined their measurement techniques in order to develop a single metric to measure annoyance affects of noise; and research continues to date.

Of the various methods available, no single method can stand alone as the best method to use. The use of any metric is highly dependent upon what one is trying to measure and/or ascertain. For example, the overall A-weighted sound level is a poor indicator of the overall annoyance affects of noise intrusion upon a certain area, but is indispensable for determining the sound insulation requirements for a building. Conversely, it is impossible to use a metric such as L_{dn} for determining acoustic insulation requirements, but is a valuable tool for developers and investors while deciding whether or not a particular area is suitable for certain types of development. The same may be said of PNL. Although PNL contours for various aircraft aren't as readily available as they were in the past, they do exist and provide an extremely useful tool to the acoustical engineer. Some of the metrics available are used solely by the

government for certifying aircraft as a means of preventing excessive noise intrusion from older or poorly maintained aircraft. These metrics [e.g. EPNL] are of little importance to the engineer in determing insulation requirements, but may be of interest in studying the physiological and psychological affects of noise on humans. In fact, every class of metric has been used in an attempt to correlate a numerical quantitiy to such effects as speech interference, sleep interference, and hearing loss. I believe an understanding of these affects is important relative to both why acoustics should be a concern in design and just exactly what one should be concerned with in order to provide a client with a good design.

One may also note, through the discussion of the fundamentals of sound, that a single overall sound level measurement says little of the quality of that sound. Recall the example listed in table 3.3. Two aircraft with the same overall SPL have significantly different spectral characteristics. Although the overall levels may be adequate for determing approximate levels of sound insulation required for a building in the conceptual design stages, they are inadequate for the final design. The spectral characteristics must be known, implying an octave band analysis is necessary. In fact, the sound absorption and insulation characteristics of acoustic

characteristics of acoustic materials are listed by octave band for this very reason. Certain materials are more effective at certain frequencies than others, thus an octave band analysis supplies the information necessary to select proper materials to provide the necessary attenuation.

In short, acoustics can be a very complex subject. But with a full understanding of the fundamentals of sound and the tools available to measure its affects, you are well on your way to acquiring the ability to provide an adequate acoustic design for any building.

APPENDIX A

NOYS AS A FUNCTION OF A-WEIGHTED SOUND PRESSURE LEVEL

NOYS AS A FUNCTION OF SOUND PRESSURE LEVEL

Band Center Frequency in Hertz (Hz)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	02	21	22	23	24	25
Lp	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12000
29																			1.0	1.0					
30																		1.0	1.0	1.1					
31																		1.1	1.1	1.1	1.0				
32																	1.0	1.1	1.2	1.2	1.1				
33																	1.1	1.2	1.3	1.3	1.2	1.0			
34																1.0	1.2	1.3	1.4	1.4	1.3	1.1			
35																1.1	1.3	1.4	1.5	1.5	1.4	1.2			
36																1.2	1.3	1.5	1.6	1.6	1.5	1.4			
37																1.3	1.4	1.6	1.8	1.8	1.6	1.5	1.0		
38															1.0	1.3	1.5	1.8	1.9	1.9	1.7	1.6	1.1		
39															1.1	1.4	1.6	1.9	2.0	2.0	1.9	1.8	1.2		
40										1.0	1.0	1.0	1.0	1.0	1.2	1.5	1.7	2.0	2.2	2.2	2.0	1.9	1.4		
41										1.1	1.1	1.1	1.1	1.1	1.3	1.6	1.8	2.2	2.4	2.4	2.2	2.0	1.5	1.0	
42									1.0	1.1	1.1	1.1	1.1	1.1	1.3	1.7	2.0	2.4	2.6	2.6	2.4	2.2	1.7	1.1	
43									1.1	1.2	1.2	1.2	1.2	1.2	1.4	1.8	2.2	2.6	2.8	2.8	2.6	2.4	1.8	1.2	
44								1.0	1.1	1.3	1.3	1.3	1.3	1.3	1.5	2.0	2.4	2.8	3.0	3.0	2.8	2.6	2.0	1.4	
45								1.1	1.2	1.4	1.4	1.4	1.4	1.4	1.6	2.1	2.6	3.0	3.2	3.2	3.0	2.8	2.2	1.5	
46							1.0	1.2	1.3	1.5	1.5	1.5	1.5	1.5	1.7	2.3	2.8	3.2	3.4	3.4	3.2	3.0	2.4	1.7	1.0
47							1.1	1.3	1.4	1.6	1.6	1.6	1.6	1.6	1.8	2.4	3.0	3.4	3.6	3.6	3.4	3.2	2.6	1.8	1.1
48						1.0	1.2	1.4	1.5	1.7	1.7	1.7	1.7	1.7	2.0	2.6	3.2	3.6	3.9	3.9	3.6	3.4	2.8	2.0	1.2
49						1.1	1.3	1.5	1.6	1.9	1.9	1.9	1.9	1.9	2.1	2.8	3.4	3.9	4.1	4.1	3.9	3.6	3.0	2.2	1.4

APPENDIX A

NOYS AS A FUNCTION OF A-WEIGHTED SOUND PRESSURE LEVEL

NOYS AS A FUNCTION OF SOUND PRESSURE LEVEL

Band Center Frequency in Hertz (Hz)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	02	21	22	23	24	25
Lp	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12000
50						1.2	1.4	1.6	1.7	2.0	2.0	2.0	2.0	2.0	2.3	3.0	3.6	4.1	4.4	4.4	4.1	3.9	3.2	2.4	1.5
51					1.0	1.3	1.5	1.7	1.9	2.1	2.1	2.1	2.1	2.1	2.4	3.2	3.9	4.4	4.7	4.7	4.4	4.1	3.4	2.6	1.7
52					1.1	1.4	1.6	1.9	2.0	2.3	2.3	2.3	2.3	2.3	2.6	3.5	4.1	4.7	5.0	5.0	4.7	4.4	3.6	2.8	1.8
53				1.0	1.2	1.5	1.7	2.0	2.1	2.5	2.5	2.5	2.5	2.5	2.8	3.7	4.4	5.0	5.3	5.3	5.0	4.7	3.9	3.0	2.0
54				1.1	1.3	1.6	1.9	2.1	2.3	2.6	2.6	2.6	2.6	2.6	3.0	4.0	4.7	5.3	5.7	5.7	5.3	5.0	4.1	3.2	2.2
55				1.2	1.4	1.7	2.0	2.3	2.4	2.8	2.8	2.8	2.8	2.8	3.2	4.3	5.0	5.7	6.1	6.1	5.7	5.3	4.4	3.5	2.3
56			1.0	1.3	1.5	1.9	2.2	2.4	2.6	3.0	3.0	3.0	3.0	3.0	3.5	4.6	5.3	6.1	6.5	6.5	6.1	5.7	4.7	3.7	2.5
57			1.1	1.4	1.7	2.0	2.4	2.6	2.8	3.2	3.2	3.2	3.2	3.2	3.7	5.0	5.7	6.5	7.0	7.0	6.5	6.1	5.0	4.0	2.8
58			1.2	1.5	1.8	2.2	2.6	2.8	3.0	3.5	3.5	3.5	3.5	3.5	4.0	5.3	6.1	7.0	7.5	7.5	7.0	6.5	5.3	4.3	3.0
59			1.3	1.7	2.0	2.4	2.8	3.0	3.2	3.7	3.7	3.7	3.7	3.7	4.3	5.7	6.5	7.5	8.0	8.0	7.5	7.0	5.7	4.6	3.3
60		1.0	1.4	1.8	2.2	2.6	3.0	3.2	3.5	4.0	4.0	4.0	4.0	4.0	4.6	6.1	7.0	8.0	8.7	8.7	8.0	7.5	6.1	5.0	3.6
61		1.1	1.5	2.0	2.4	2.8	3.2	3.5	3.7	4.3	4.3	4.3	4.3	4.3	5.0	6.5	7.5	8.7	9.3	9.3	8.7	8.0	6.5	5.3	3.9
62		1.2	1.7	2.2	2.6	3.0	3.5	3.7	4.0	4.6	4.6	4.6	4.6	4.6	5.3	7.0	8.0	9.3	10	10	9.3	8.7	7.0	5.7	4.2
63		1.3	1.8	2.4	2.8	3.2	3.7	4.0	4.3	4.9	4.9	4.9	4.9	4.9	5.7	7.5	8.7	10	11	11	10	9.3	7.5	6.1	4.6
64	1.0	1.5	2.0	2.6	3.0	3.5	4.0	4.3	4.6	5.3	5.3	5.3	5.3	5.3	6.1	8.0	9.3	11	11	11	11	10	8.0	6.5	5.0
65	1.1	1.6	2.2	2.8	3.2	3.7	4.3	4.6	5.0	5.7	5.7	5.7	5.7	5.7	6.5	8.7	10	11	12	12	11	11	8.7	7.0	5.3
66	1.2	1.8	2.4	3.0	3.5	4.0	4.6	5.0	5.4	6.1	6.1	6.1	6.1	6.1	7.0	9.3	11	12	13	13	12	11	9.3	7.5	5.7
67	1.4	2.0	2.6	3.3	3.7	4.3	5.0	5.4	5.9	6.5	6.5	6.5	6.5	6.5	7.5	10	11	13	14	14	13	12	10	8.0	6.1
68	1.6	2.2	2.8	3.6	4.0	4.6	5.4	5.9	6.4	7.0	7.0	7.0	7.0	7.0	8.0	11	12	14	15	15	14	13	11	8.7	6.5
69	1.8	2.3	3.0	3.9	4.3	5.0	5.9	6.4	6.9	7.5	7.5	7.5	7.5	7.5	8.7	11	13	15	16	16	15	14	11	9.3	7.0

APPENDIX A

NOYS AS A FUNCTION OF A-WEIGHTED SOUND PRESSURE LEVEL

NOYS AS A FUNCTION OF SOUND PRESSURE LEVEL

Band Center Frequency in Hertz (Hz)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	02	21	22	23	24	25
Lp	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12000
70	2.0	2.5	3.3	4.2	4.6	5.4	6.4	6.9	7.5	8.0	8.0	8.0	8.0	8.0	9.3	12	14	16	17	17	16	15	12	10	7.5
71	2.2	2.8	3.6	4.6	5.0	5.9	6.9	7.5	8.0	8.6	8.6	8.6	8.6	8.6	10	13	15	17	19	19	17	16	13	11	8.0
72	2.3	3.0	3.9	5.0	5.4	6.4	7.5	8.0	8.7	9.2	9.2	9.2	9.2	9.2	11	14	16	19	20	20	19	17	14	11	8.7
73	2.5	3.3	4.2	5.4	5.9	6.9	8.0	8.7	9.3	9.8	9.8	9.8	9.8	9.8	11	15	17	20	21	21	20	19	15	12	9.3
74	2.8	3.7	4.6	5.9	6.4	7.5	8.7	9.3	10	10.6	10.6	10.6	10.6	10.6	12	16	19	21	23	23	21	20	16	13	10
75	3.0	4.1	5.0	6.4	6.9	8.0	9.3	10	11	11.3	11.3	11.3	11.3	11.3	13	17	20	23	24	24	23	21	17	14	11
76	3.3	4.5	5.4	6.9	7.5	8.7	10	11	11	12	12	12	12	12	14	19	21	24	26	26	24	23	19	15	11
77	3.7	5.0	5.9	7.5	8.3	9.3	11	11	12	13	13	13	13	13	15	20	23	26	28	28	26	24	20	16	12
78	4.1	5.4	6.4	8.3	9.1	10	11	12	13	14	14	14	14	14	16	21	24	28	30	30	28	26	21	17	13
79	4.5	5.9	6.9	9.1	10	11	12	13	14	15	15	15	15	15	17	23	26	30	32	32	30	28	23	19	14
80	5.0	6.4	7.5	10	11	11	13	14	15	16	16	16	16	16	19	24	28	32	35	35	32	30	24	20	15
81	5.5	6.9	8.3	11	11	12	14	15	16	17	17	17	17	17	20	26	30	35	37	37	35	32	26	21	16
82	6.1	7.5	9.1	11	12	13	15	16	17	18	18	18	18	18	21	28	32	37	40	40	37	35	28	23	17
83	6.8	8.3	10	12	13	14	16	17	19	20	20	20	20	20	23	30	35	40	42	42	40	37	30	24	19
84	7.5	9.1	12	13	14	15	17	19	20	21	21	21	21	21	24	32	37	42	45	45	42	40	32	26	20
85	8.3	10	13	14	15	16	19	20	21	23	23	23	23	23	26	35	40	45	47	47	45	42	35	28	21
86	9.1	12	13	15	16	17	20	21	23	24	24	24	24	24	28	37	42	47	50	50	47	45	37	30	23
87	10	13	14	16	17	19	21	23	24	26	26	26	26	26	30	40	45	50	55	55	50	47	40	32	24
88	11	13	15	17	19	20	23	24	26	28	28	28	28	28	32	42	47	55	60	60	55	50	42	35	26
89	12	14	16	19	20	21	24	26	28	30	30	30	30	30	35	45	50	60	63	63	60	55	45	37	28

APPENDIX A

NOYS AS A FUNCTION OF A-WEIGHTED SOUND PRESSURE LEVEL

NOYS AS A FUNCTION OF SOUND PRESSURE LEVEL

Band Center Frequency in Hertz (Hz)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	02	21	22	23	24	25
Lp	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12000
90	14	15	17	20	21	23	26	28	30	32	32	32	32	32	37	47	55	63	67	67	63	60	47	40	30
91	15	16	19	21	23	24	28	30	32	34	34	34	34	34	40	50	60	67	71	71	67	63	50	42	32
92	16	17	20	23	24	26	30	32	35	37	37	37	37	37	42	55	63	71	75	75	71	67	55	45	35
93	17	19	21	24	26	28	32	35	37	39	39	39	39	39	45	60	67	75	80	80	75	71	60	47	37
94	19	20	23	26	28	30	35	37	40	42	42	42	42	42	47	63	71	80	86	86	80	75	63	50	40
95	20	21	24	28	30	32	37	40	42	45	45	45	45	45	50	67	75	86	93	93	86	80	67	55	43
96	21	23	26	30	32	35	40	42	45	49	49	49	49	49	55	71	80	93	100	100	93	86	71	60	46
97	23	24	28	32	35	37	42	45	47	52	52	52	52	52	60	75	86	100	108	108	100	93	75	63	50
98	24	26	30	35	37	40	45	47	50	56	56	56	56	56	64	80	93	108	116	116	108	100	80	67	55
99	26	28	32	37	40	42	47	50	55	60	60	60	60	60	69	86	100	116	125	125	116	108	86	71	60
100	28	30	35	40	42	45	50	55	60	64	64	64	64	64	74	93	108	125	133	133	125	116	93	75	63
101	30	32	37	42	45	47	55	60	64	69	69	69	69	69	79	100	116	133	142	142	133	125	100	80	67
102	32	35	40	45	47	50	60	64	69	74	74	74	74	74	84	108	125	142	150	150	142	133	108	86	71
103	35	37	42	47	50	55	64	69	74	79	79	79	79	79	91	116	133	150	162	162	150	142	116	93	75
104	37	40	45	50	55	60	69	74	79	84	84	84	84	84	97	125	142	162	173	173	162	150	125	100	80
105	40	42	47	55	60	64	74	79	84	91	91	91	91	91	104	133	150	173	186	186	173	162	133	108	86
106	42	45	50	60	64	69	79	84	91	97	97	97	97	97	111	142	162	186	200	200	186	173	142	110	93
107	45	47	55	64	69	74	84	91	97	104	104	104	104	104	119	150	173	200	215	215	200	186	150	125	100
108	47	50	60	69	74	79	91	97	104	111	111	111	111	111	128	162	186	215	232	232	215	200	162	133	108
109	50	55	64	74	79	84	97	104	111	119	119	119	119	119	137	173	200	232	250	250	232	215	173	142	116

APPENDIX A

NOYS AS A FUNCTION OF A-WEIGHTED SOUND PRESSURE LEVEL

NOYS AS A FUNCTION OF SOUND PRESSURE LEVEL

Band Center Frequency in Hertz (Hz)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	02	21	22	23	24	25
Lp	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12000
110	55	60	69	79	84	91	104	111	119	128	128	128	128	128	147	186	215	250	266	266	250	232	186	150	125
111	60	64	74	84	91	97	111	119	128	137	137	137	137	137	158	200	232	266	284	284	266	250	200	162	133
112	64	69	79	91	97	104	119	128	137	147	147	147	147	147	169	215	250	284	300	300	284	266	215	173	142
113	69	74	84	97	104	111	128	137	147	158	158	158	158	158	181	232	266	300	324	324	300	284	232	186	150
114	74	79	91	104	111	119	137	147	158	169	169	169	169	169	194	250	284	324	346	346	324	300	250	200	162
115	79	84	97	111	119	128	147	158	169	181	181	181	181	181	208	266	300	346	372	372	346	324	266	215	173
116	84	91	104	119	128	137	158	169	181	194	194	194	194	194	223	284	324	372	400	400	372	346	284	232	186
117	91	97	111	128	137	147	169	181	194	208	208	208	208	208	239	300	346	400	430	430	400	372	300	250	200
118	97	104	119	137	147	158	181	194	208	223	223	223	223	223	256	324	372	430	464	464	430	400	324	266	215
119	104	111	128	147	158	169	194	208	223	239	239	239	239	239	274	346	400	464	500	500	464	430	346	284	232
120	111	119	137	158	169	181	208	223	239	256	256	256	256	256	294	372	430	500	532	532	500	464	372	300	250
121	119	128	147	169	181	194	223	239	256	274	274	274	274	274	315	400	464	532	568	568	532	500	400	324	266
122	128	137	158	181	194	208	239	256	274	294	294	294	294	294	338	430	500	568	600	600	568	532	430	346	284
123	137	147	169	194	208	223	256	274	294	315	315	315	315	315	362	464	532	600	648	648	600	568	464	372	300
124	147	158	181	208	223	239	274	294	315	338	338	338	338	338	388	500	568	648	692	692	648	600	500	400	324
125	158	169	194	223	239	256	294	315	338	362	362	362	362	362	416	532	600	692	744	744	692	648	532	430	346
126	169	181	208	239	256	274	315	338	362	388	388	388	388	388	446	568	648	744	800	800	744	692	568	464	372
127	181	194	223	256	274	294	338	362	388	416	416	416	416	416	478	600	692	800	860	860	800	744	600	500	400
128	194	208	239	274	294	315	362	388	416	446	446	446	446	446	512	648	744	860	928	928	860	800	648	532	430
129	208	223	256	294	315	338	388	416	446	478	478	478	478	478	549	692	800	928	1000	1000	928	860	692	568	464

APPENDIX A

NOYS AS A FUNCTION OF A-WEIGHTED SOUND PRESSURE LEVEL

NOYS AS A FUNCTION OF SOUND PRESSURE LEVEL

Band Center Frequency in Hertz (Hz)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	02	21	22	23	24	25
Lp	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12000
130	223	239	274	315	338	362	416	446	478	512	512	512	512	512	588	744	860	1000	1064	1064	1000	928	744	600	500
131	239	256	294	338	362	388	446	478	512	549	549	549	549	549	630	800	928	1064	1136	1136	1064	1000	800	648	532
132	256	274	315	362	388	416	478	512	549	588	588	588	588	588	676	860	1000	1136	1200	1200	1136	1064	860	692	568
133	274	294	338	388	416	446	512	549	588	630	630	630	630	630	724	928	1064	1200	1296	1296	1200	1136	928	744	600
134	294	315	362	416	446	478	549	588	630	676	676	676	676	676	776	1000	1136	1296	1384	1384	1296	1200	1000	800	648
135	315	338	388	446	478	512	588	630	676	724	724	724	724	724	832	1064	1200	1384	1488	1488	1384	1296	1064	860	692
136	338	362	416	478	512	549	630	676	724	776	776	776	776	776	891	1136	1384	1488	1600	1600	1488	1384	1136	928	744
137	362	388	446	512	549	588	676	724	776	832	832	832	832	832	955	1200	1488	1600	1720	1720	1600	1488	1200	1000	800
138	388	416	478	549	588	630	724	776	832	891	891	891	891	891	1024	1296	1600	1720	1856	1856	1720	1600	1296	1064	860
139	416	446	512	588	630	676	776	832	891	955	955	955	955	955	1098	1384	1720	1856	2000	2000	1856	1720	1384	1136	928
140	446	478	549	630	676	724	832	891	955	1024	1024	1024	1024	1024	1176	1488	1856	2000			2000	1856	1488	1200	1000
141	478	512	588	676	724	776	891	955	1024	1098	1098	1098	1098	1098	1261	1600	2000					2000	1600	1296	1064
142	512	549	630	724	776	832	955	1024	1098	1176	1176	1176	1176	1176	1351	1720							1720	1384	1136
143	549	588	676	776	832	891	1024	1098	1176	1261	1261	1261	1261	1261	1448	1856							1856	1488	1200
144	588	630	724	832	891	955	1098	1176	1261	1351	1351	1351	1351	1351	1552	2000							2000	1600	1296
145	630	676	776	891	955	1024	1176	1261	1351	1448	1448	1448	1448	1448	1663									1720	1384
146	676	724	832	955	1024	1098	1261	1351	1448	1552	1552	1552	1552	1552	1783									1836	1488
147	724	776	891	1024	1098	1176	1351	1448	1552	1663	1663	1663	1663	1663	1911									2000	1600
148	776	832	955	1098	1176	1261	1448	1552	1663	1783	1783	1783	1783	1783											1720
149	832	891	1024	1176	1261	1351	1552	1663	1783	1911	1911	1911	1911	1911											2000
150	891	955	1098	1261	1351	1448	1663	1783	1911																

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